RESONANT RADIATION EFFECTS ON MOVING
STRIATIONS IN AN ARGON GLOW DISCHARGE

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ABSTRACT

The effect of metastable atom concentrations on moving striations in

an argon glow discharge was studied by the technique of irradiative de-

population   Attempts were made to determine the time rate of change of

the argon metastable atom concentration in the moving striations by

measurement of the absorption of resonant wavelengths and by detection

of the increased emission after absorption. Changes induced in the vari-

ous parameters of the discharge, when irradiated with resonant energy,

were also studied. The effect on moving striations due to irradiative

depopulation of the metastable states of argon by external resonant

radiation was found to be of considerable significance. It is shown that

the existence of the moving striations exhibits a profound dependence on

the concentration of metastable argon atoms existing in the positive

column of an argon glow discharge. This work lends considerable sup-

port to existing theories of two-stage ionization processes in glow dis-

charges containing the noble gases

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1. Introduction.

1.1 Background.

Many studies have been made of direct current glow discharges in the rare gases and mercury vapor. The characteristic features of such discharges include the Cathode glow, Cathode dark space, Negative glow, Faraday dark space and uniformly glowing Positive column. Even though the positive column may appear completely stable, to the eye its behavior is far from simple. With a current-pressure product in a certain range, moving striations are a common property of the positive column.

Many attempts have been made to explain the existence and properties of moving striations. To date, no adequate theory exists. The classical approach to an explanation of moving striations has been to use the theory of plasma oscillations. This approach has not been noted for its success. A fairly complete review and analysis of plasma oscillations is presented by Francis (1).

Recent theoretical attempts to explain moving striations attribute the striation phenomena to space charge waves associated with the production and loss of ions. Watanabe and Oleson (2) showed that traveling waves of ion and electron densities can exist in the positive column. Their calculations are based on a constant ionization rate per electron. The simplified expressions representing the traveling density waves have frequencies and wavelengths which are widely different from the usual plasma oscillations. It is not claimed that moving striations are related to such waves in view of the assumptions required to obtain solutions. However, it does show

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that ionization waves may exist in the positive column of a glow discharge.

Robertson (3) has proposed a theory based on the continuity equations for the positive ions, the negative ions, and the metastable excited atoms in the discharge. This is the first mathematical approach which specifically includes the metastable concentrations and the corresponding production and loss processes.

The predictions of this theory are as follows:

(1) When a spatially uniform plasma is considered, a high concentration of metastable atoms may be necessary to produce instability in the positive column.

(2) Examination of ion balance equations for wave - like solutions results in:

(a) traveling density waves similar to those predicted by Watanabe and Oleson, when variations in the metastable concentration are ignored, and

(b) traveling density waves dependent on production and loss processes which can travel in either direction depending upon conditions in the plasma, when all diffusion processes are ignored.

This theory has not been carried to the point where predictions of measurable parameters can be made. The major difficulties seem to be lack of ionization and excitation rates, especially those associated with the metastable atoms, and the electron distribution function.

1.2 Evidence to Support the Role of Metastable Atoms.

In 1950, Kenty (4) studied the role of the metastable $(^3P_2)$ mercury atom in low current discharges. It was noted that strong illumination of the discharge with a second mercury discharge nearly doubled the tube

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potential, doubled the electron temperature, doubled the 2537 A line intensity, and nearly suppressed the ordinary running (moving) striations. These effects are explained on the basis of destruction of the mercury metastables by the resonant radiation, the striations in pure mercury apparently being dependent on two stage ionization involving the production of metastable atoms.

Donahue and Dieke (5) also propose a two stage ionization process involving the production of metastable atoms. This process is proposed as a possible explanation for the phase lag of up to 20 microseconds between the excitation of the 2537 A line and the 4358 A line observed in moving striations in mercury.

Further evidence, although not directly concerned with moving striations, has been furnished by Meissner and Miller (6) in their experiments involving resonant radiation with the various rare gases. By irradiating He, Ne, A, and Xe discharges with discharges containing the same gases, they showed a definite increase in the discharge tube potential (at constant current) in each case. In He, they showed that this increase was due entirely to the 20,852A resonant line, which will cause depopulation of the metastable state. For argon, the increase in the discharge tube potential was considerably greater than for the other gases. They attribute this large increase to the very long lifetime of the argon metastable atoms. Unfortunately, they did not investigate the effect on the moving striations, but the effects on the discharge tube potential are in agreement with those found by Kenty (4) working with mercury.

Pekarek (10), working with neon, also observed changes in the parameters (such as velocity of propagation and wavelength) of both the slow waves (positive striations) and the fast waves (negative striations) when the experimental discharge was irradiated with another neon discharge. He also reports an increase in amplitude of the fast wave and a decrease in amplitude of the slow wave. In this work, he concludes that this evidence supports the view that the slow waves involve a stepwise ionization process involving metastable atoms, while the fast waves involve direct ionization.

Hakeem and Robertson (8) performed experiments with plasmas of K, Rb, and Cs, none of which have metastable states, examining in particular for the presence of the moving striations. They reported that at no time were moving striations observed. They used discharge tubes with diameters of from 1 to 3 cm and 20 to 30 cm between electrodes, at pressures from 0.01 to 2.0 mm Hg and a current range from 0 to 400 ma. They did observe anode spot oscillations moving into the positive column and attenuating within 1 cm of the anode.

Hakeem and Robertson (9) have recently observed effects of irradiative depopulation of metastables in neon. They were able to produce moving striations in neon by irradiating an experimental discharge with a second neon discharge when there were initially no moving striations in the experimental discharge. They were also able to destroy moving striations in the experimental tube by irradiation when initially the experimental discharge did have moving striations present. In the first case, the experi-

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tube contained 0 83 mm Hg pressure with 5 ma of current and the latter case was with 10 ma of current at the same pressure. They also reported striking changes in the striation pattern in the experimental discharge when changing the illumination level of irradiation on a length of only 4.5 cm at the cathode end of the positive column.

Our experimental observations are assessed as being qualitatively in agreement with the predictions of the Robertson theory. These effects are measured in our own work with argon. Qualitative information is obtained in relation to the mechanism proposed by Robertson.

1.3 The Present Problem.

In view of the evidence to support the interrelation between the metastable atoms and moving striations, this work has been undertaken in an effort to determine the metastable concentration within the moving striations and the phase relationship between the maximum metastable concentration and the moving striation maximum light intensity. From this it is expected that some measure of the excitation and ionization rates of metastable atoms may be obtained.

In addition, investigations are performed by irradiating sections of the positive column in argon and the changes in the striation and discharge behavior are noted. There is considerable correlation between the effects demonstrated by Kenty (4) in mercury vapor and those reported by Hakeem and Robertson (9) in neon. Further work is necessary in order that the effects in the other rare gases may possibly be correlated with those already demonstrated in mercury and neon

2. Experimental Equipment.

   2.1 <u>Vacuum System</u>.

   A schematic diagram of the vacuum system is shown in Fig. 1.

This system was constructed by A. W. Cooper in 1959. The principle com-

ponents of the system include two cold traps, one high vacuum bakable

valve situated so that the discharge tube can be isolated from the rest of

the system, an 80 cm octoil manometer, one diffusion pump, one fore pump,

two gas bottles and an ionization gage. This system is capable of reduc-

ing the pressure in the discharge tube to about 5×10^{-7} mm Hg.

   All discharge tubes were connected to the vacuum system after

they had been baked at a temperature of 400° C for periods ranging from 16

to 24 hours. The electrodes in the tubes were heated to a bright red-orange

color with a Scientific Electric Co. induction heater in order to drive off dis-

solved gases and other impurities. The discharge tube was then filled with

approximately 5 mm Hg pressure of argon and the discharge started. While

the discharge was running, the tube was pumped down very slowly. This

procedure was carried out several times before the final gas at the required

pressure was placed in the tube and measurements taken. The discharge

tubes were normally filled after the system had been evacuated to a pres-

sure between 8×10^{-7} and 2×10^{-6} mm Hg. This vacuum provided a rela-

tively pure discharge and was considered adequate for the experiments.

   The pressure in the system (before filling) was determined by the

use of a Consolidated Electrodynamics Corp. ionization gage, type DPA-38

with a VG-1A sensing tube, for high vacuum measurements. The gas

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VACUUM SYSTEM

CEC VG IA

MANOMETER 60 CM OCTOIL

ARGON BOTTLES

LIQUID AIR TRAP

LIQUID AIR TRAP

DISCHARGE TUBE   CEC VAU 25

CVC GF 20 A DIFFUSION PUMP
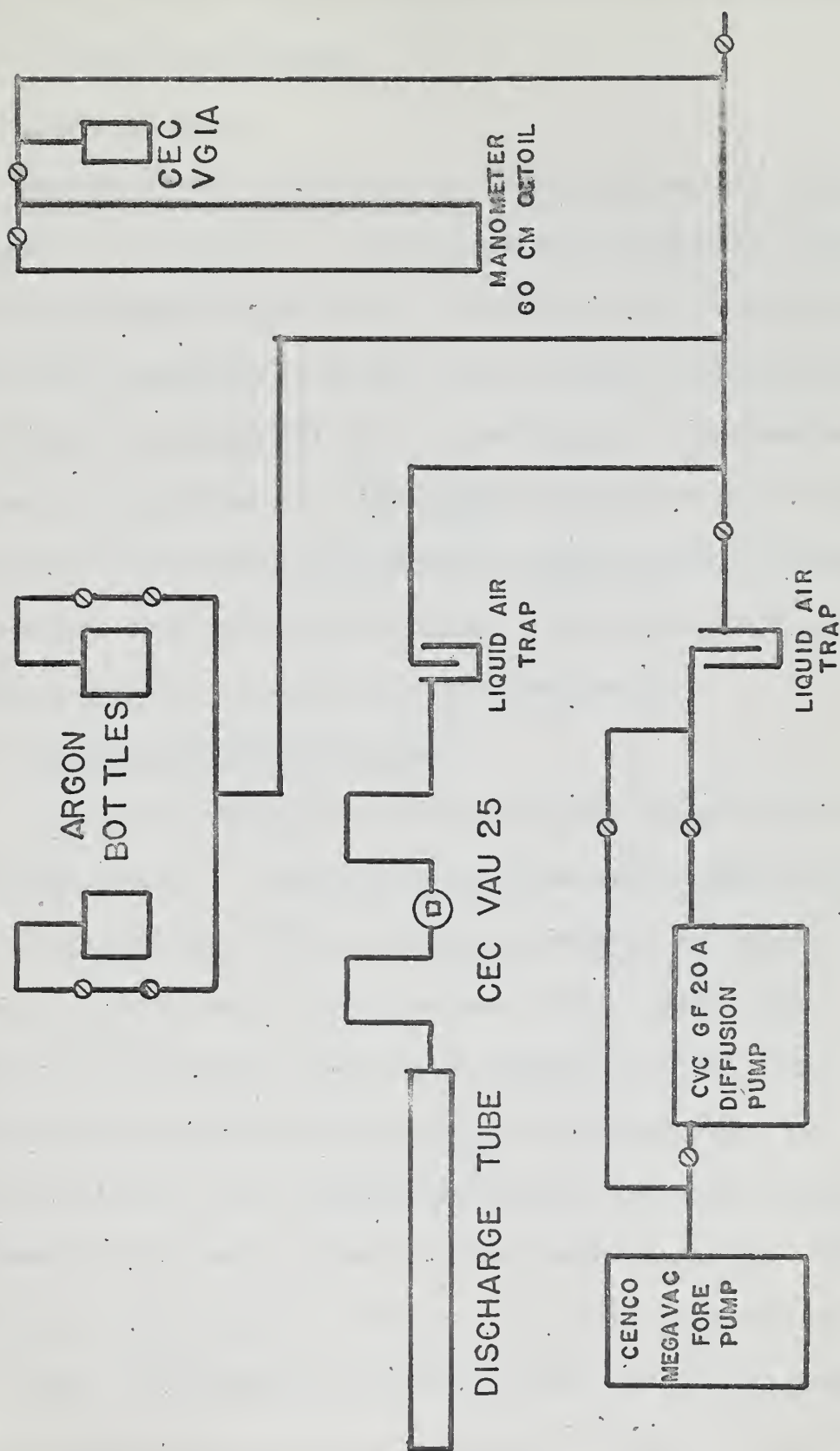
CENCO MEGAVAC FORE PUMP

FIGURE 1

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pressure in the tube after filling was measured on the octoil manometer (1 cm of oil equals 0.725 mm Hg).

2.2 Discharge Tubes.

Details of the construction of the discharge tubes used in this experiment are shown in Fig. 2. All filaments were constructed of tungsten and spot welded to nickel leads. The cylinders used for the auxiliary discharge were constructed of nickel and spot welded to tungsten supports. All electrodes were constructed so as to permit Pupp's anode operation using either end of the discharge tube. This practice doubles the tube life since either electrode may be used as the anode or cathode simply by reversing the direction of current flow through the tube. Thus filament failure on one end does not destroy the usefulness of the discharge tube.

2.3 Discharge Circuit and Equipment.

A schematic diagram of the discharge circuit and associated equipment is shown in Fig. 3. Electrical power for the main discharge was furnished by a Kepco model 770B power supply, providing a regulated dc voltage of up to 600 volts and 2.5 amps maximum. When higher voltages were necessary, two such power supplies were connected in series. Three resistor banks were connected in series with the main discharge. Two of these resistor banks inserted resistance by means of two-way switches and allowed for the insertion of two 3.6 kohm, variable resistors. With all resistance in these banks in the circuit, the total resistance amounted to 172.2 kohm. The third resistor bank consisted of five decade resistor boxes which permitted the insertion of additional resistance of up to 555.5

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Fig. 2. Discharge Tube Construction

Tube A

2.1 cm

76 cm

2.5 cm

3 cm

Tube B

3.8 cm

72 cm

2 cm

2 cm
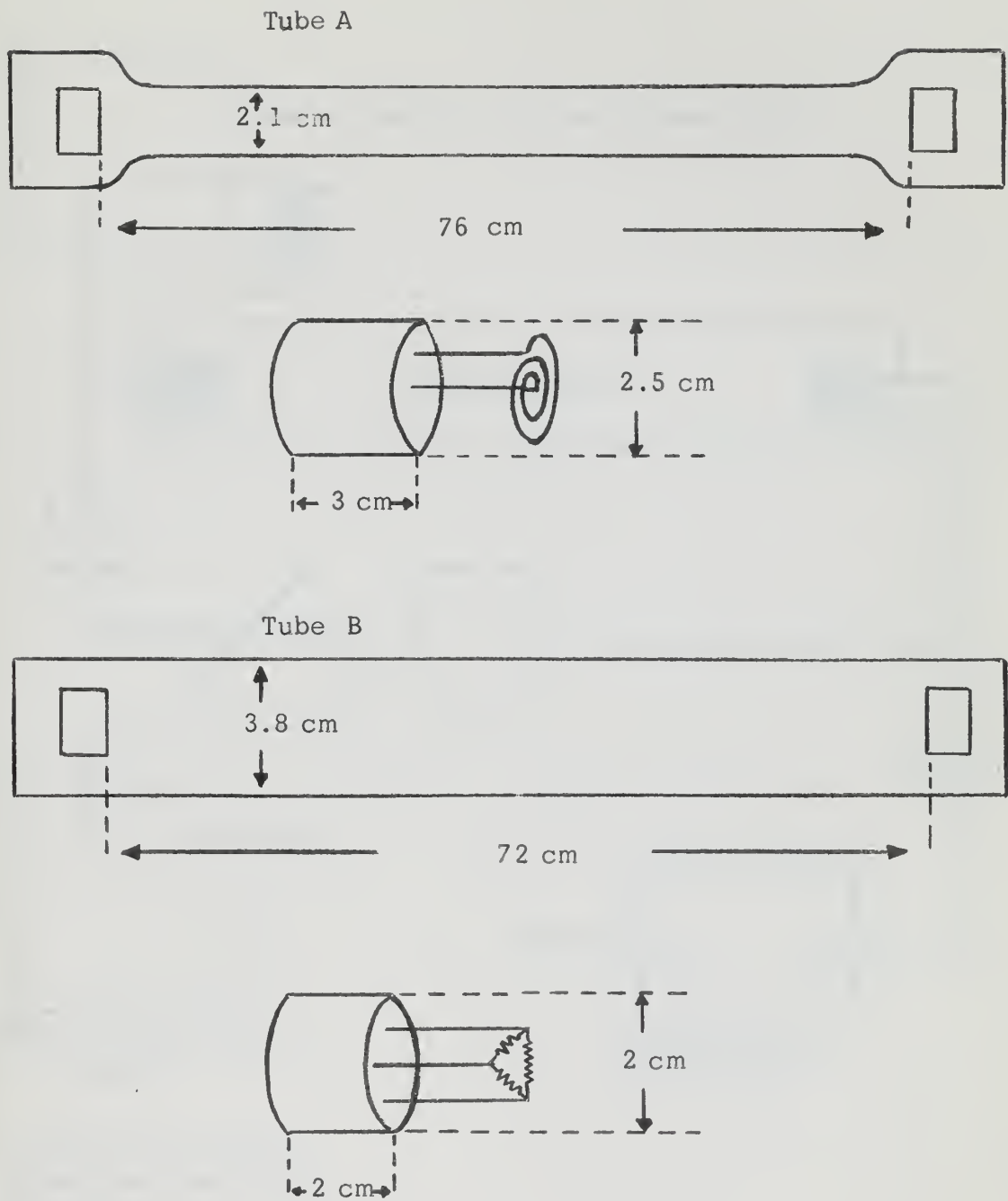
Cylinders and Leads – Nickel
Cylinder Supports   – Tungsten
Filaments   – Tungsten

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Auxiliary (anode) Discharge Power Supply

Discharge Tube

Main Discharge Power
    Supply

Cathode Heating
Power Supply
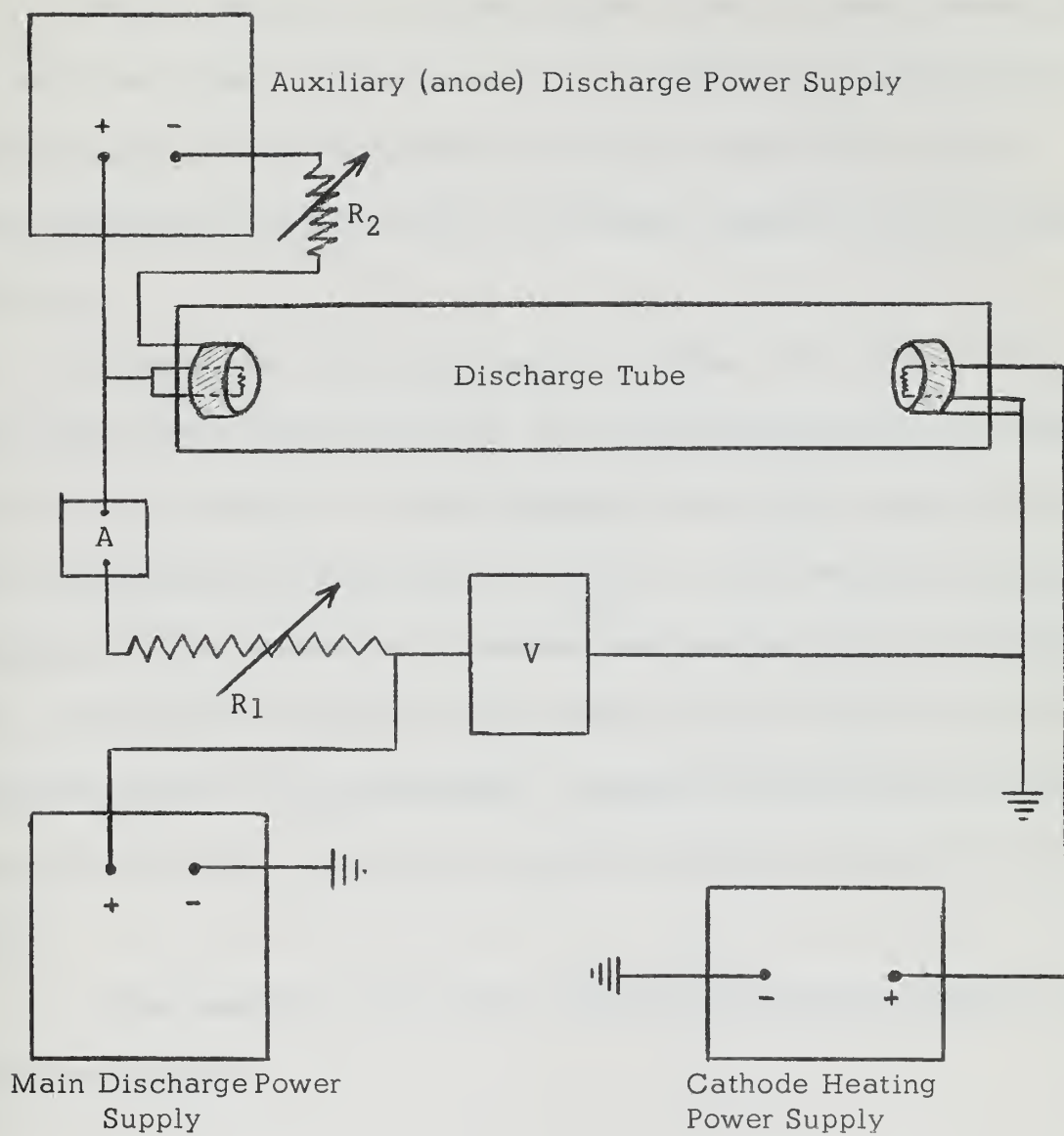
R_1 Ballast Resistance
R_2 Auxiliary Resistance
A   Ammeter
V   Voltmeter

Fig. 3. Discharge Circuit

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kohms. For operation at very low currents, a supply voltage of approxi-
mately 1000 volts and practically all the resistance afforded by the circuit
was found to be necessary.

When operating the discharge above 100 ma, a directly heated cath-
ode was always used. Below this value, the cathode was operated hot or
cold as required. Power for cathode heating was provided by a Kepco,
model KM 236-15A, dc power supply, providing a maximum of 35 volts and
15 amps.

For operation of the Pupp's anode, a Kepco, model 605, voltage
regulated dc power supply was used. This supply provided up to 600 volts
and 0.5 amps maximum. The anode discharge was usually operated with
100 volts or more and with currents up to 300 ma. This auxiliary discharge
produces a high concentration of electrons and positive ions in the anode
fall region which eliminates the anode oscillations by allowing the positive
column to extend to the anode surface. Cooper's (13) work gives a complete
analysis of the relationship between anode oscillations and moving stria-
tions.

Other equipment used in this work will be described in detail in the
appropriate section.

3. Techniques for the Measurement of Striation Metastable Concentration.

3.1 Theory.

Atoms in excited states generally make optical transitions to lower states in times of the order of 10^{-8} seconds. Unless election densities are very high, few collisions with excited atoms occur in this time. Exceptions to this general rule are the atoms in metastable states which are forbidden to make dipole transitions to lower states and therefore may exist for much longer times. In particular, the mean metastable lifetime for argon in a normal glow discharge is about 3.5 milliseconds (6).

The argon metastable levels, the 4s(1 $\frac{1}{2}$) and the 4s'(1/2) are shown in Fig. 4; optical transitions associated with these levels are shown on an enlarged section of this diagram in Fig. 5. The term resonant radiation will be used when referring to radiation having the discrete photon energy required to promote an atom from a metastable state to a higher excited state. The optical transition into a metastable state corresponds to the resonant wavelength which will promote transitions out of the metastable state.

An atom may be removed from a metastable state to the ground state by providing radiation at the resonant wavelength which will excite the metastable to an excited state of higher energy from which a dipole transition to the ground state is allowed. The transitions to the ground state may be direct or via an intermediate state. The probability of exciting this atom to a higher excited state is greatest when the resonant wavelength selected corresponds to the highest relative intensity of the optical transition into the metastable state. For example, exciting a metastable argon atom with resonant radiation

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Fig. 4. Argon I Grotrian Diagram (Prepared by R. L. Kelly)

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Fig.5

Optical Transitions Associated with the Argon I
Metastable Levels. AIP Notation (7).
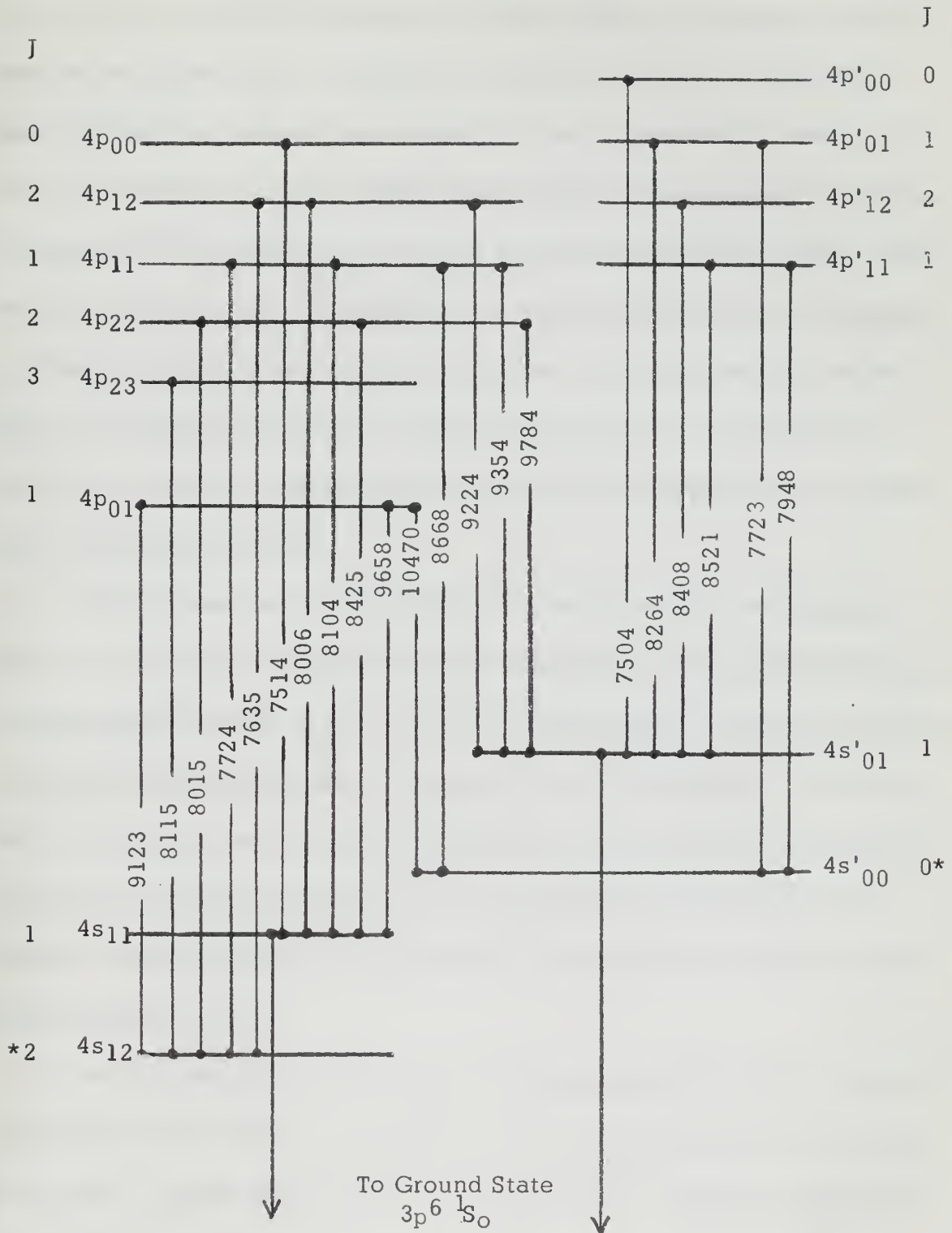
at 7635A will cause a transition from the $4s_{12}$ metastable level to the $4p_{12}$ level (see Fig. 5). From the $4p_{12}$ level, dipole transitions to ground are allowed via the $4s_{11}$ level emitting the 8006A line, or via the $4s'_{01}$ level emitting the 9224A line. If a beam of resonant radiation at 7635A were passed through an unknown concentration of argon metastable atoms, the amount of radiation absorbed would theoretically furnish enough information to determine the concentration of atoms in the $4s_{12}$ metastable state. Also, the increased emission of the 8006A line and the 9224A line would furnish an indication of the concentration. Therefore, the 7635A resonant wavelength can provide an indication of the metastable atom concentration by emission of radiation in depopulation or by loss of energy from the incident beam of resonant radiation.

Not all resonant wavelengths will destroy the argon metastable atoms. For example, the 8115A resonant wavelength will excite the atom to the $4p_{23}$ level (see Fig. 5), but the only allowed dipole transition is back to the original metastable level with reemission of the 8115A line. Therefore, the 8115A resonant wavelength would not destroy the metastable atoms but the amount of radiation absorbed at this wavelength would theoretically provide enough information to determine the concentration of atoms in the $4s_{12}$ metastable state.

Another phenomenon with argon is the depopulation of the metastable $4s_{12}$ state which results in an increase in the population of the metastable $4s'_{00}$ state. The reverse process is also possible. Resonant radiation at 9123A will excite metastable atoms from the $4s_{12}$ level to the $4p_{01}$ level

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(see Fig. 5) from which transitions to ground are allowed via the $4s_{11}$ level, emitting 9658A radiation or to the $4s'_{00}$ metastable level emitting 10470A.

One of the major objectives of this work was to determine the concentration of metastable atoms within the moving striations, and the phase relationship between the maximum metastable concentration and the maximum striation light intensity. As previously mentioned, (section 1.1) one of the main limitations of the Robertson (3) theory is the lack of ionization and excitation rates for the metastable atoms. The time rate of change of the metastable concentration in the striated argon glow discharge would possible furnish enough data to obtain a functional form for these rates.

The two approaches used to determine the metastable concentration were: (1) detecting the attenuation by the striated discharge of a uniform beam of radiation at a resonant wavelength, and (2) detecting the increased emission from the level to which the metastables have been excited by resonant radiation.

3.2 <u>Absorption Technique</u>.

The 8115A resonant wavelength was used because it is the strongest resonant line, as indicated by the relative intensity in Table I. This resonant wavelength will not alter the metastable concentration as described in Section 3.1; however, the absorption from an incident beam at this wavelength will provide a measure of the metastable concentration. Since the transition probability is proportional to the intensity of the transition, this resonant line should theoretically show the greatest absorption as compared to the other argon resonant lines (see Table 1).

Table 1

Relative Intensities for the Optical Transitions in Figure 5.

Wavelength (Angstroms)	Transition AIP (a)		Intensity AIP (b)	Detectable Intensity (c)
	Upper State	Lower State		
7503.867	$4p'_{00}$	$4s'_{01}$	0.96	0.59
7514.651	$4p_{00}$	$4s_{11}$	0.93	0.56
7635.105	$4p_{12}$	$4s_{12}$	0.99	1.00
7723.760	$4p'_{01}$	$4s'_{00}$	0.97	(0.48
7724.206	$4p_{11}$	$4s_{12}$	-	(
7948.175	$4p'_{11}$	$4s'_{00}$	0.92	0.36
8006.156	$4p_{12}$	$4s_{12}$	0.94	0.27
8014.786	$4p_{22}$	$4s_{12}$	0.95	0.47
8103.692	$4p_{11}$	$4s_{11}$	0.95	0.43
8115.311	$4p_{23}$	$4s_{12}$	1.00	1.00
8264.522	$4p'_{01}$	$4s'_{01}$	0.95	0.24
8408.209	$4p'_{12}$	$4s'_{01}$	0.96	0.34
8424.647	$4p_{22}$	$4s_{11}$	0.96	0.43
8521.443	$4p'_{11}$	$4s'_{01}$	0.93	0.17
8667.944	$4p_{11}$	$4s'_{00}$	0.81	0.03
9122.966	$4p_{01}$	$4s_{12}$	-	0.18
9224.496	$4p_{12}$	$4s'_{01}$	-	0.05
9354.218	$4p_{11}$	$4s'_{01}$	-	-
9657.784	$4p_{01}$	$4s_{11}$	-	0.02
9784.501	$4p_{22}$	$4s'_{01}$	-	-
10470.051	$4p_{01}$	$4s'_{00}$	-	-

(a) AIP (American Institute of Physics) notation.

(b) Relative intensities from the American Institute of Physics Handbook.

(c) Relative intensities using the RCA 7102 phototube and the Baird grating monochromator with 750 micron slits.

Shown in Fig. 6 is the equipment arrangement used to detect the attenuation of a beam of resonant wavelength passed through the striations. Two phototubes, PM-1 and PM-2, were arranged in such a manner that each would receive identically the same changing light signal from the moving striations. The phototube responses were sent to a low level ac differential amplifier where the signals canceled each other. Then a beam of constant light intensity at a resonant wavelength selected by the monochromator was passed through the positive column to PM-2. If the constant intensity of this incident beam were modulated by absorption due to the changing metastable concentration, PM-2 would have a modulated signal superimposed on the changing light signal from the moving striations. Since the changing light signal from the moving striations would be cancelled at the differential amplifier by the signal from PM-1, the modulated signal should be presented on the oscilloscope. This modulated resonant signal would then give an indication of the time rate of change of the metastable population within the moving striation and the phase relationship between the maximum metastable concentration and the maximum striation light intensity.

All attempts to apply this technique gave inconclusive results. The primary limiting factor was the ability to obtain a source of sufficient strength at the desired resonant wavelength. Each component of the experimental setup will be discussed separately, emphasizing the capabilities and limitations. Recommendations to improve this approach are also considered.

The Amplifier.

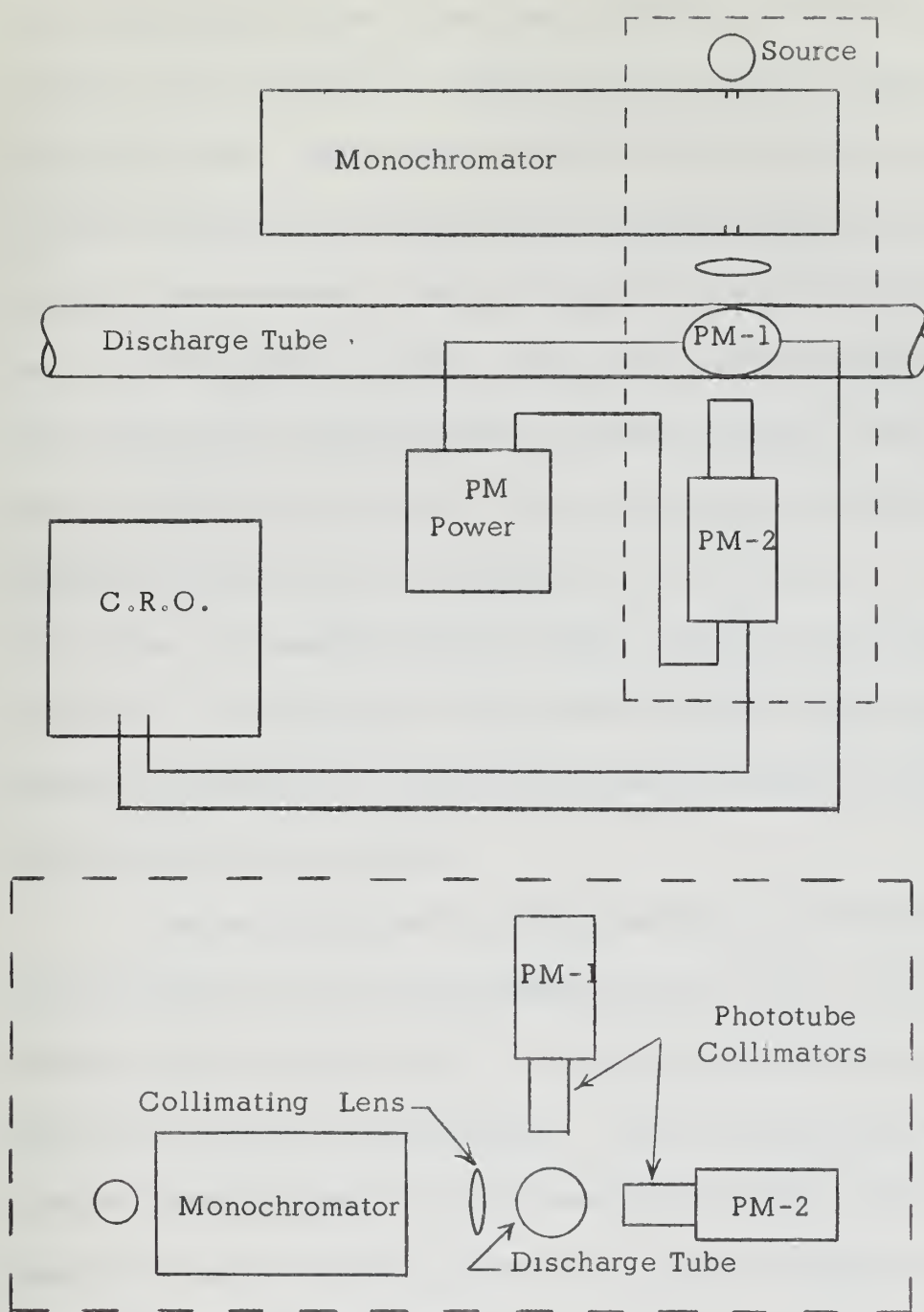The Tektronix 551 oscilloscope with a Tektronix low-level differen-

Fig. 6. Equipment Arrangement for the Absorption Technique.

tial ac preamplifier type E, was used to amplify and display the waveforms. The 551 'scope contains two electron beams controlled by the same x-deflection system. This design permitted the modulated signal to be presented on one beam and an independent striation pattern on the other beam for phase measurements. The type E unit has a sensitivity of 50 microvolts per cm to 10 millivolts per cm in eight fixed calibrated positions which are also continuously variable between the fixed positions, thus extending the range up to 25 millivolts per cm. This unit provided an adjustable high-frequency response with 3 db points at 50 cps, 250 cps, 1 kc, 10 kc, and 20 to 60 kc. For exactly inphase signals, this unit has a rejection ratio of 50,000 to 1. The maximum common-mode signal amplitude which can be canceled satisfactorily is about 2 volts peak-to-peak, if there is no dc associated with these signals.

The responses from the phototubes were sent to the differential amplifier using the circuit arrangement shown in Fig. 7. All leads were shielded and of minimum length. The blocking capacitors are as large as practical to prevent signal distortion. Low noise, precision resistors were used for bleeding current from the capacitors to ground. The blocking capacitors and the bleeder resistors were placed in a mumetal box to prevent pickup of stray signals.

Calibration of the differential preamp was accomplished using two inphase 2 volt peak-to-peak square wave signals from the oscilloscope calibrator. These signals were sent through the above circuit and could be canceled with a maximum deflection of 10 microvolts of noise presented on

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Fig. 7. Photomultiplier Circuitry
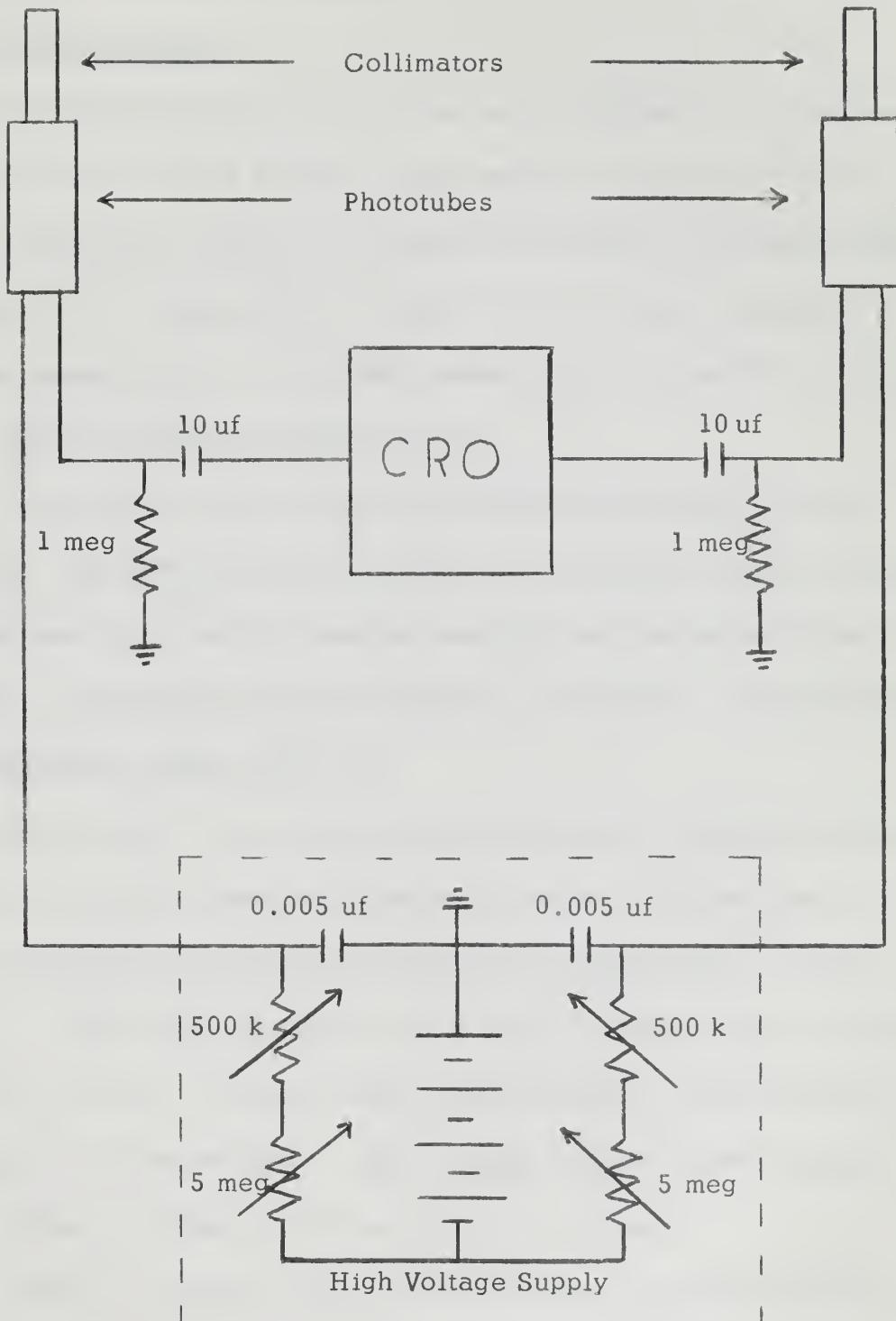
the oscilloscope screen. The 10 microvolts of noise represented 0.2 cm of deflection using the differential preamp 50 microvolts/cm sensitivity position (highest sensitivity available).

Photomultipliers.

The RCA 7102 photomultiplier tube was used because its spectral sensitivity response has a maximum value between 7000A and 9000A (see Fig. 8). This range of sensitivity contains the majority of the wavelengths considered for use in measuring the population of the argon metastable levels, as shown in Fig. 5. The characteristic curve for the 7102 at various values of dynode voltage is shown in Fig 9.

The phototube cases and dynode circuits were made by Eldorado Electronics. The cases provided a heavy mumetal shield for the phototube. Other phototube cases without mumetal shielding were tested but showed considerably greater noise and less stability at the output. The dynode circuit arrangement is shown in Fig. 10.

High voltage for the phototubes was provided by using four Burgess V200, 300 volt dry cell batteries connected in series. The necessary circuitry to provide two isolated but variable high voltage outputs is shown in Fig. 7. This arrangement provided a smooth dc high voltage variable from 800 to 1200 volts. Lower voltages, when desired, could be obtained by removing one of the batteries. High voltage electronic power supplies were unsatisfactory because of the ac ripple at the output.

Light from a narrow section of the discharge was selected with a pair of narrow slits 8 cm apart, mounted in front of the photocathode. This
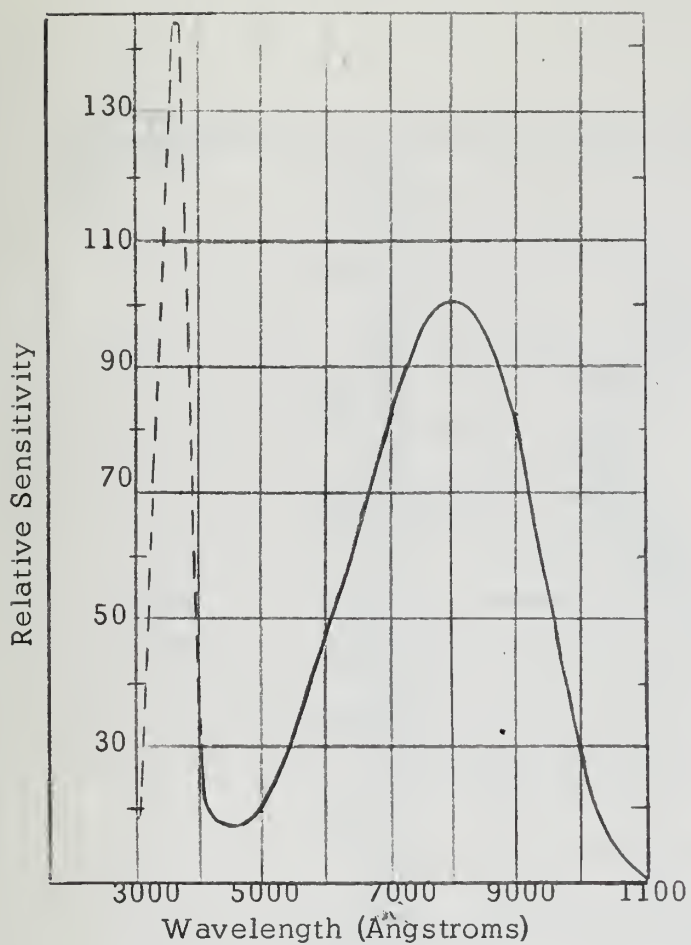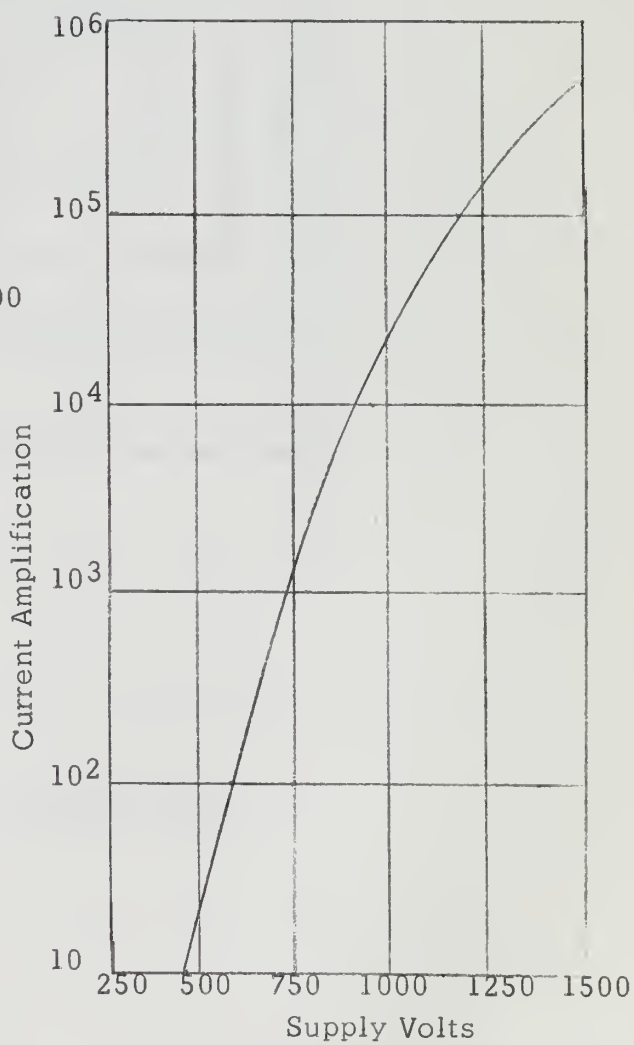
Fig. 8. Spectral Response
        Characteristics of
        RCA 7102 Photomultiplier

Fig. 9. Characteristics of RCA
        7102 Photomultiplier

Fig. 10. Phototube Dynode Circuit

R_1 through R_{10} 460k
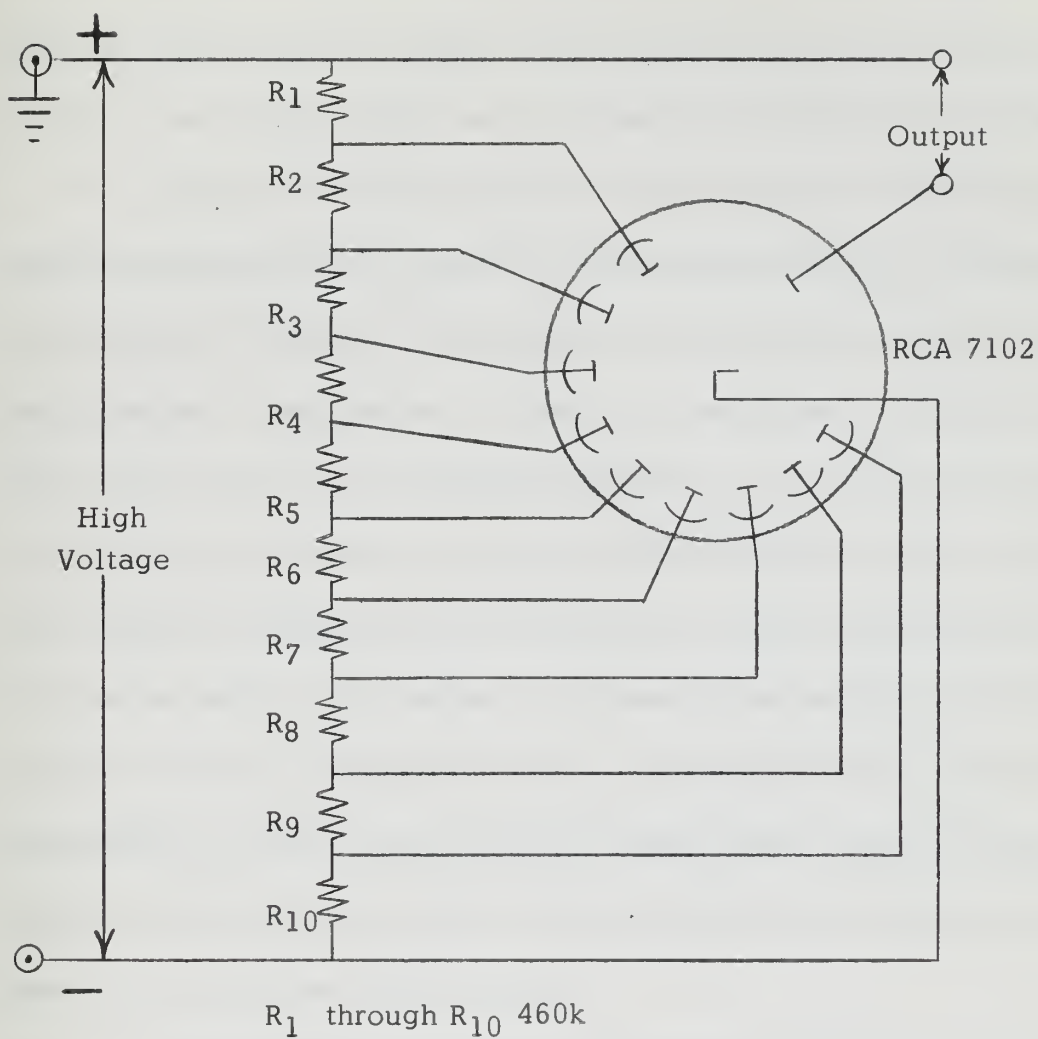
simple collimating system prevented stray reflections from reaching the photocathode and also maintained the light intensity to the photocathode within the limits for linear and stable operation. For linear operation, the ratio of anode current to voltage divider current should not exceed 0.1. For stability, the average anode current should be well below 10 microamperes.

Since the ultimate objective was to measure a small modulated signal superimposed on a relatively large striation signal, the dark current noise and the "light noise" associated with phototube measurements were of major concern. Dark current, or thermionic emission, is produced by electrons emitted from the photocathode because it is at a finite temperature. The electrons are emitted in a random fashion, and give rise to dark current noise which is proportional to the square root of the dark current (11, 12). In a similar manner, light noise is produced by the random emission of the electrons from the photocathode due to incident light and is proportional to the square root of the light intensity. Refrigeration of the phototube reduces the dark current and dark current noise, but there is no way of reducing the light noise at a given light intensity.

The important quantity to be measured is the signal-to-noise ratio. Since the light noise increases only as the square root of the intensity, the signal to noise ratio can be improved by increasing the light intensity. This is shown by the following relation (11).

$$(s/n)^2 = i_p^2 \Big/ 2\underline{e}\ (\triangle f)\ (i_p + i_t)$$

where s/n is the signal to noise ratio, $\underline{e}$ the electron charge, Δf the bandwidth of the amplifier and associated circuits, i_p photo-current produced by the light, and i_t the dark current. If the light intensity is increased by a factor of four, the signal-to-noise ratio will be doubled provided that the dark current noise is much less than the light noise. If the dark current is appreciable, the signal-to-noise ratio will be greater, but this implies that the signal-to-noise ratio was originally quite low. For any given range of light levels to be measured, it is desirable that the limiting factor in detectability or precision of the measurement be light noise and not dark current noise.

Dark current and dark current noise for the phototubes are tabulated in Table 2. The dark current is measured directly where the dark current noise is the peak-to-peak deflection presented on the oscilloscope for various values of dynode voltage. The important quantity is the peak-to-peak deflection presented on the oscilloscope (to be referred to hereafter as noise) with both phototubes operating at a dynode voltage which will give the same response to a changing light signal. This is also tabulated in Table 2. PM-1 required a dynode voltage 50 volts greater to match the ac response of PM-2.

An indication of the magnitude of light noise was obtained by having two in-phase light signals canceled at the preamp and observing the noise presented on the oscilloscope as the dynode voltage was increased. For example, a 200 millimicroampere peak-to-peak striation response (determined with a dynode voltage of 1000) would indicate a noise level greater

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Table 2

Phototube Dark Current and Dark Current Noise.

Dynode Voltage	Dark Current Millimicroamps		Dark Current Noise (a) Microvolts		Dark Current Noise Microvolts
	PM-1	PM-2	PM-1	PM-2	PM-1 plus PM-2 (b)
850	0 9	1 0	25	20	30
900	1.0	1.0	25	25	40
950	1.1	1.1	30	40	55
1000	1.5	1.2	50	60	85
1050	2.0	1.4	75	100	140
1100	3.2	1.9	150	200	210
1150	5.6	3.0	275	300	370
1200	14 0	5.7	400	475	610

(a) Peak-to-peak oscilloscope deflection..

(b) PM-1 operating with a dynode voltage 50 volts

greater than PM-2.

than the dark current noise with dynode voltages at 750 volts. For a corre-
sponding 100 millimicroampere response, the noise level would exceed the
dark current noise with the dynodes at 900 volts. In the first case, the com-
bined noise level would be about 300 microvolts for the dynodes at 950 volts
and the second case about 150 microvolts at the same dynode voltage. Add-
ing a constant light signal to PM-2 equal to the peak-to-peak striation
response would degreade the response of PM-2 considerably. A constant light
signal equal to about 50% of the striation response would not degrade the
response of PM-2 enough to be detected but would increase the combined
noise by about 30%. A constant light signal corresponding to 20% of the
peak-to-peak striation response, would increase the total noise by about 10%.
Taking into consideration the noise levels, the dynode voltage limits were
selected between 800 and 1000 volts depending on the peak-to-peak stria-
tion signal.

The critical factor to consider in obtaining satisfactory conditions
for detection of a modulated signal superimposed on the striation signal was
the ratio of the striation signal to the constant resonant light signal. (Stria-
tion signals were determined in terms of peak-to-peak detectable phototube
current as calculated from the oscilloscope deflections. Constant light sig-
nals were measured directly with a differential photometer, Eldorado Elec-
tronics Model 210.) If the above ratio is less than two, the phototube
response is degraded. If the ratio is greater than ten, the modulated signal
will be hidden in the total noise presented on the oscilloscope.

Discharge Conditions.

One of the major discharge requirements was a steady striation pattern over a fairly wide current range   The conditions selected, in terms of current and pressure, were 50 to 500 milliamperes and 3 to 8 mm Hg. Cooper's (13) work furnished excellent data for the striation parameters with these operating conditions   The striation frequency was generally less than 1 kc so the 1 kc frequency response setting of the differential preamp could be used when desired   This frequency response attenuated the striation waveform to a small degree; however   the reduction in high frequency noise was considerable.   The discharge was generally operated hot cathode and an anode auxiliary discharge was used at all times to prevent anode oscillations.

With the above discharge conditions, the striation peak-to-peak phototube response could be varied from 50 to 500 millimicroamperes.   These values are well below the maximum usable signal for the phototube and the differential preamp.

Monochromator.

A Baird Associates one meter grating monochromator was used to select specific resonant wavelengths.   The grating was blazed for maximum transmission of wavelengths from 35,000A to 45,000A which corresponds to the fifth order of diffraction for the argon lines of interest.   A Corning Glass Works infrared transmitting filter, C.S   Number 7-69, was used at the monochromator input to eliminate interference from other orders of undesired wavelengths.   The spectral transmission curve of this filter is shown in Fig. 11. The monochromator would resolve specific spectral lines within $\pm$ 3A with
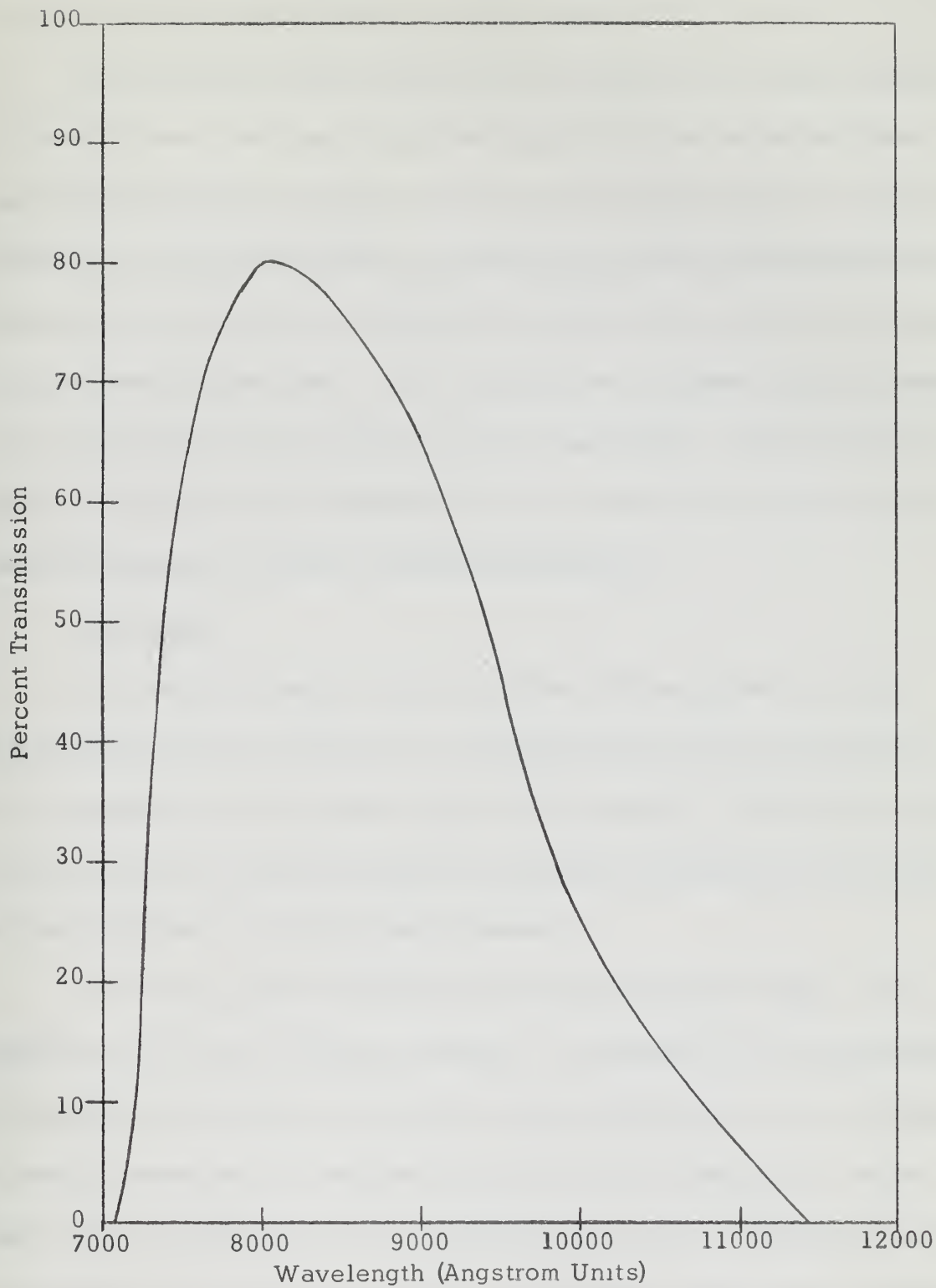
Fig. 11

Transmission Efficiency of Corning Infrared Transmitting,
Visible Absorbing Filter (7-69).

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75 micron slits and within $\pm$ 8A with 750 micron slits.

The resonant radiation from the monochromator was passed through a collimating lens, and then through the positive column to the phototube which had a collimating arrangement in front of the photocathode as described previously. Approximately 20% of the energy leaving the monochromator was detectable at the phototube. Preliminary alignment was accomplished visually using the mercury green line. Final alignment was completed using a phototube as the detector for the desired resonant wavelength. The detectable resonant energy was measured directly in terms of phototube current with a differential photometer, Eldorado Electronics Model 210.

The Source.

As stated previously, the ratio of the striation signal to the constant resonant radiation signal has to be greater than two but less than ten for the modulation of the resonant signal to be detected. The striation signals range from 50 to 500 millimicroamperes, therefore, the desired resonant signal should be from 5 to 250 millimicroamperes.

The initial source selected was a tungsten filament lamp. Since tungsten acts as a near blackbody radiator, it appeared to be convenient from the standpoint of intensity and uniform energy distribution. For a blackbody, the energy emitted per unit wavelength interval has a maximum at a wavelength which depends only on the temperature of the body. To obtain maximum radiation in the vicinity of 8000A, the blackbody temperature required is about 3600°K using Wien's displacement law, or a corresponding tungsten temperature of 3450°K using data from Forsythe and Watson (14).

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Various types of tungsten lamps were built and tested, but a temperature of 3450°K was never attained. The best tungsten lamp for maximum temperature and uniform energy distribution was the General Electric (Microscope-illuminator 18A-T10 SR 8 filament) ribbon filament lamp. This lamp could operate at about 3050°K for extended periods. At this temperature, the maximum detectable constant light signal was 150 millimicroamperes (dynode voltage 1000 V) when using 750 micron monochromator slits. This would have been a satisfactory constant light signal if it could have been restricted to the resonant wavelength. Since the tungsten spectrum is continuous, this detectable energy was distributed over at least $\pm$ 8A at the desired wavelength. Assuming a regular contour for the distribution of the energy at the monochromator exit slit, less than 10% of this energy is within a unit wavelength at the desired wavelength selected by the monochromator. This is unsatisfactory in terms of phototube detection because all of this energy excites the photocathode while only a fraction of the energy is sufficiently near the desired transition frequency to exhibit resonant absorption.

The only practical source that would eliminate the undesirable distribution of energy shown by tungsten is an argon source. Even though excited gases show relatively weak spectra, the argon resonant wavelengths could be separated by the monochromator so that the majority of the energy detected by the photocathode would be at the resonant wavelength. A Central Scientific Co. argon spectral tube was used and excited with dc power and with a 45 Mc rf oscillator. With the rf oscillator it was possible to obtain approximately twice the radiant energy obtained by exciting the

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the argon with 1000 volts dc. The maximum detectable energy attained was 2 millimicroamperes (the minimum desired was 5 millimicroamperes) using the Central Scientific Co. spectral tube excited with the rf oscillator. The intensity of this source is limited by vapors released from the glass at high excitation currents. These vapors produce spectra which obscure the argon spectrum.

Various discharge conditions were investigated using the 2 milli-microampere resonant signal; however, under all conditions the modulated signal, if present, was obscured in the phototube noise. Refrigerating the phototubes may reduce the total noise to a level where detection is possible in a very limited range of discharge conditions. The time available did not permit a study of this possible improvement.

Summary.

The primary limitation of the absorption technique, as applied in this work, was the ability to obtain a source of sufficient intensity at the desired resonant wavelength. Only 20% of the energy leaving the mono-chromator is detectable at the desired phototube, but this is one of the balancing factors for this approach. Most of the energy lost during the transfer from the monochromator to the phototube is due to the size and separation of the collimating slits in front of the photocathode. Making these slits larger would increase the energy transferred; however, it would also increase the striation signal to the photocathode. The ratio of striation signal to constant resonant signal would remain about the same but the photocathode would have a larger total signal and a small modulated signal would be even more

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difficult to detect. Therefore, the only foreseeable improvement in the ratio

of striation signal to constant resonant signal would be to increase the

source intensity. Refrigerating the phototubes may reduce the total phototube

noise, as presented on the oscilloscope, sufficiently that a modulated signal

could be detected when using the maximum constant resonant signal obtained

from the spectral tube. This improvement, if indeed the total phototube noise

is substantially reduced, would be limited to a small range of discharge con-

ditions.

The fact that the total striation signal is impressed on the photo-

cathode leads to the requirement for an intense source. The authors do not

believe that it will be possible to obtain a source of sufficient intensity to

apply the absorption technique as described above. An improved absorption

technique will be outlined later in this paper. This improved approach will

effectively reduce the striation signal to the photocathode thereby eliminat-

ing the requirement for a more intense source.

3.3 _Emission Technique_.

When a metastable atom is destroyed by resonant radiation, there

will be energy emitted from a higher excited state as the atom returns to the

ground state via allowed transitions as described in Section 3.1. For ex-

ample, irradiating a narrow section of the positive column with the 8015A

resonant wavelength would excite metastables from the $4s_{12}$ to the $4p_{22}$

level (see Fig. 5). The metastable atoms excited to the $4p_{22}$ level can re-

turn to the ground state via the $4s_{11}$ level emitting 8425A or via the $4s'_{01}$

level emitting 9784A. If enough metastable atoms are excited to this higher

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energy state in a narrow section of the positive column, it should theoret-ically be possible to detect the increased emission of the 8425A or 9784A line.

The equipment arrangement for detecting this increased emission when metastable atoms are destroyed is shown in Fig. 12. Two monochrom-ators, M-1 and M-2 with phototubes PM-1 and PM-2, are set up so that each would receive the same emission wavelength from the moving striations. The monochromators are separated by one wavelength (striation spacing) since emission of radiation occurs in all directions. The phototube responses are fed to the differential preamp where the signals cancel each other. Then an intense beam of constant light intensity at a resonant wavelength selected by the filter is passed through a narrow section of the positive column in the same region where monochromator M-1 is selecting the desired emission wave-length. If the metastables are destroyed in the vicinity of monochromator M-1, PM-1 should detect a greater emission signal than PM-2. This additional emission signal would be presented on the oscilloscope. A detailed analy-sis of the 'scope presentation and the original striation wave form would give an indication of the metastable concentration.

Theoretically this approach is sound. However, the number of metastable atoms that would need to be destroyed is very high since the re-sulting emission spectrum lines are radiated throughout 4π sterradians. Of the total emission due to destruction of metastable atoms, approximately 1/5000th could enter the monochromator and be detected by the phototube. Since the phototube signal is initially very small, one discrete wavelength
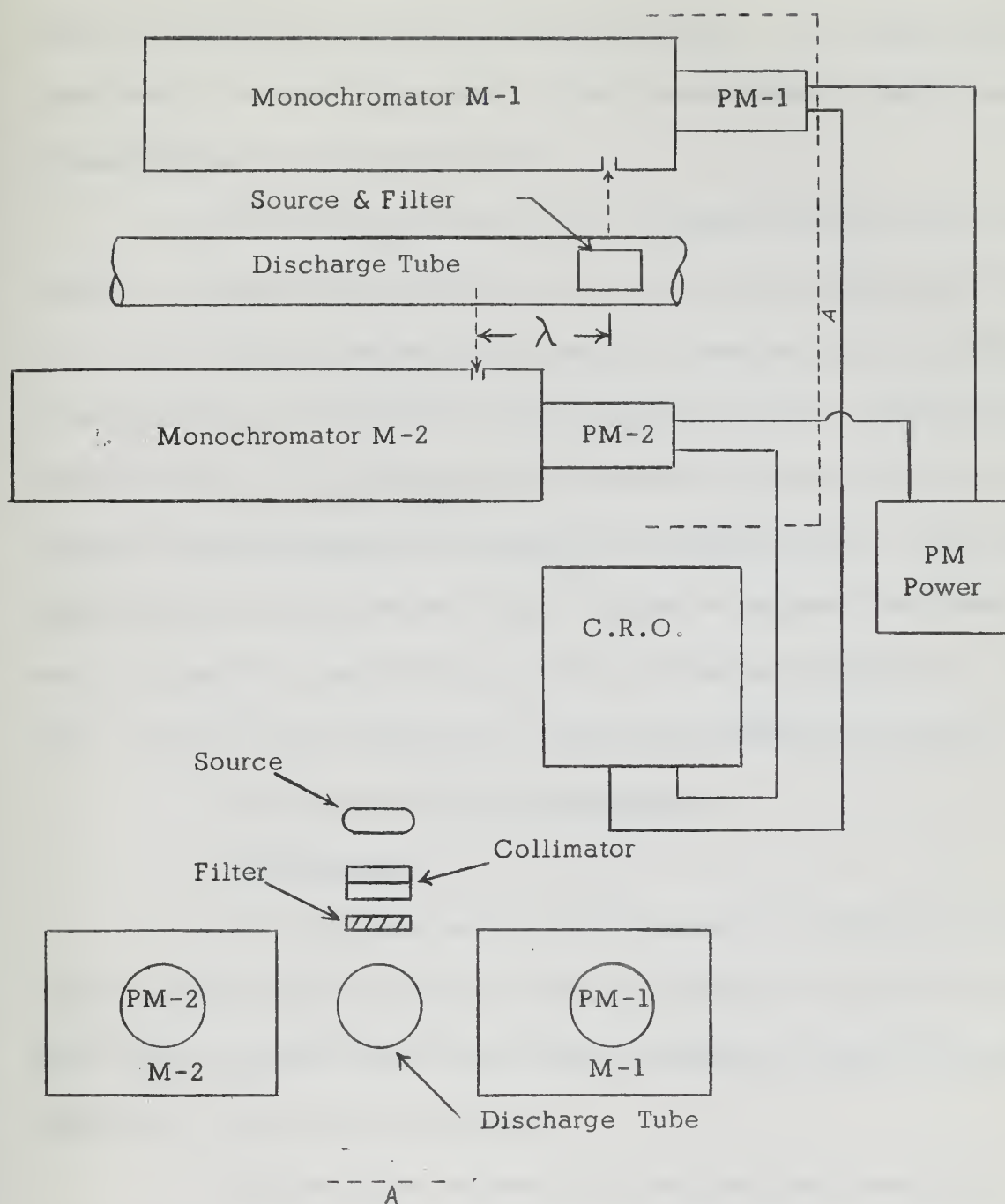
Fig. 12. Equipment Arrangement for the Emission Technique.

compared to the entire striation signal for the absorption technique, an additional small signal should be readily detectable. This approach was undertaken to see if it is possible to detect the additional radiation caused by depopulation of a metastable state.

The initial limiting factor for this technique was the ability to construct an additional monochromator with characteristics matched with those of the Baird grating monochromator described in Section 3.2. This additional monochromator was constructed using available materials. A Bausch and Lomb Optical Co. 600 grooves per mm unblazed grating was mounted on a suitable platform separated one meter from the adjustable slits. Even with adjustable slits, using various orders of the argon resonant wavelengths, it was not possible to match the outputs from the two monochromators. Therefore, no results were obtained and no qualitative analysis is possible.

3.4. Conclusions and Recommendations.

Conclusions.

No conclusive results were obtained in our efforts to measure the metastable population within the moving striations. It is hoped that further studies may benefit from the problems encountered in this work while attempting to make such measurements.

In view of the evidence which supports the role of metastable atoms in a striated glow discharge (see Section 1.2 and Section 4 of this report), the importance of determining the time rate of change for the metastable concentration is clear. To date all the evidence presented is in terms of the overall effects on the striated discharge parameters. If an ade-

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quate theory is to be devised which will explain the existence and behavior of moving striations, it is imperative that the excitation and ionization rates for metastable atoms be determined. The time rate of change of the metastable concentration should provide sufficient information to obtain these rates.

Recommendations.

An improved absorption technque is believed to be the simplest approach that can be used to obtain accurate measurements of the time rate of change of the metastable population in a striated glow discharge. Shown in Fig. 13 is the equipment arrangement for this approach. The equipment requirements and procedure are similar to those described in Section 3.2. The main differences are: (1) the use of two matched monochromators which are arranged to receive an identical single resonant wavelength from the striations, and (2) the use of a filter to select the resonant wavelength desired. These changes provide the following improvements: (1) selecting a single resonant line from the striations reduces the signal to the photocathode by as much as two orders of magnitude, and (2) using a filter to select the constant resonant signal will decrease the energy lost in the transfer process.

The ratio of striation signal to constant resonant signal can readily be controlled due to the location of the source in relation to monochromator M-1 (see Fig. 13) which will detect the striation signal and the resonant signal. This arrangement eliminates the requirement for a very intense source. The spectral tube described in Section 3.2 should be adequate for
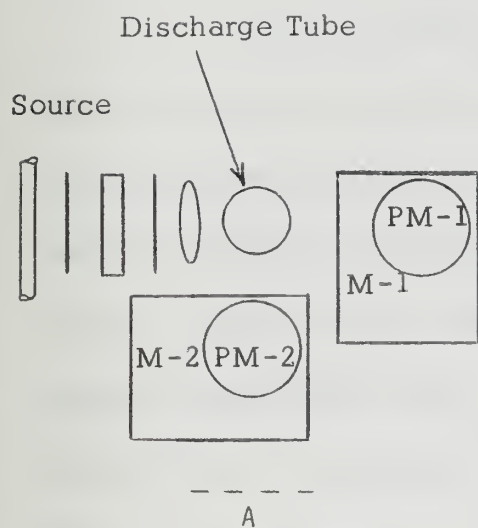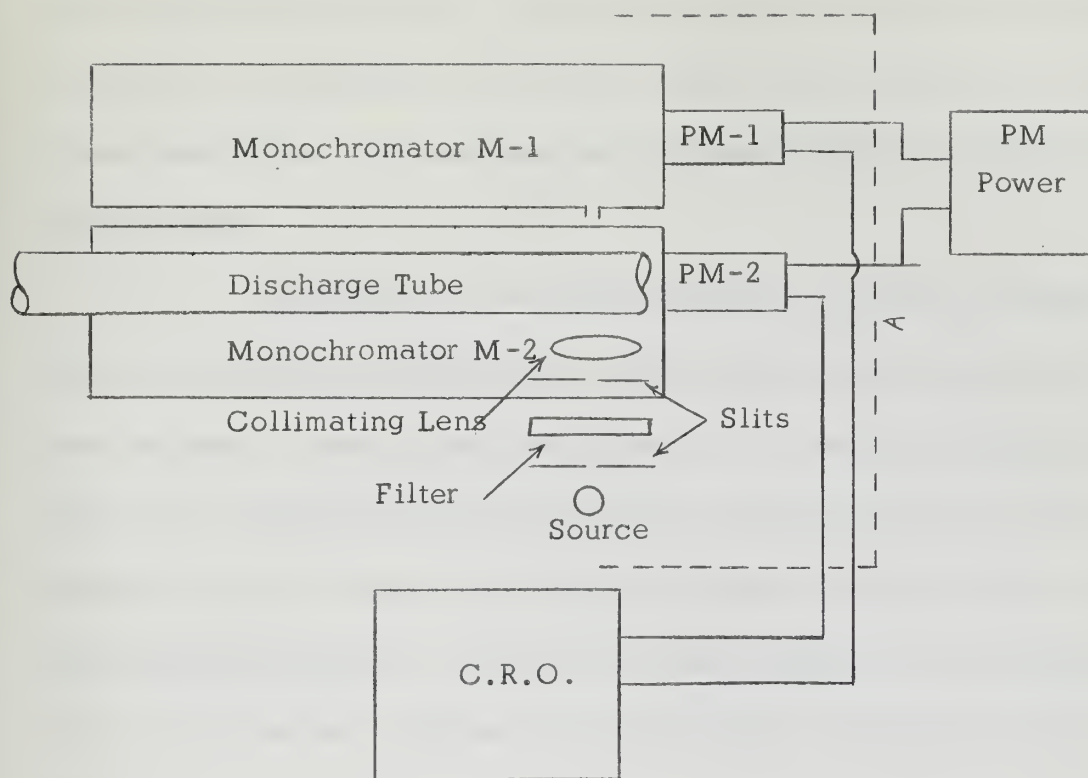
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Monochromator M-1

PM-1

PM Power

Discharge Tube

PM-2

Monochromator M-2

Collimating Lens

Slits

Filter

Source

C.R.O.

A

Discharge Tube

Source

PM-1

M-1

M-2 PM-2

A

Fig. 13. Recommended Equipment
Arrangement for the
Absorption Technique.

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preliminary investigations. A source which will provide greater intensity, if required, is described by Ryde (16). This source contains two closely spaced electrodes, the discharge being viewed through a hollow cathode or hollow anode.

The limits on the ratio of striation signal to resonant signal were previously required due to the large striation signal impressed on the photocathode. Since the striation signal for this modified approach is very small, it is estimated that the above ratio may be as small as 1/10 (the resonant signal 10 times greater than the striation signal) without degrading the phototube response. In view of the small signals on the photocathode, it may be advisable to refrigerate the phototubes to reduce the dark current noise.

The monochromators need to be matched and should be able to resolve specific spectral lines within $\pm 8A$. Narrow bandpass filters are required for selecting the resonant wavelengths. Since 8115A is the most desirable resonant wavelength for absorption studies, a filter which will transmit maximum energy at this wavelength and absorb the nearest other resonant wavelength, 8015A, (see Fig. 5), is required. This will prevent the destruction of metastable atoms in the $4s_{12}$ state (see Fig. 5) while absorption measurements are being made. The absorption of the 7635A resonant line may be used; however, this resonant wavelength will cause depopulation of the $4s_{12}$ states and may cause changes in the striation waveform.

4. Resonant Radiation Effects.

4.1 Previous Work.

Since 1950, several investigators have shown that gross effects can be produced in a discharge tube containing any of the noble gases, or mercury, when the discharge is illuminated with a second discharge containing the same gas. Kenty (4), in 1950, was among the first to note these effects, but Meissner and Miller (6), Donahue and Dieke (5), Hakeem and Robertson (9), and Pekarek (10) have all reported similar events since that time. Unfortunately, Meissner and Miller were concerned only with the potential change across the discharge tube when it was irradiated. However, they did observe this effect in all of the noble gases except radon. The other investigators used only neon, with the exception of Donahue and Dieke and Kenty. Donahue and Dieke used several of the rare gases and also mercury vapor. Kenty confined his experiments to observations of the phenomena that occurred in mercury vapor when irradiated with a second discharge. There appears to be good correlation among the results reported.

In general, the observed effects of resonant radiation are as follows: (1) an increase in the discharge tube potential at constant current; (2) changes in the frequency, wavelength and velocity of the moving striations; (3) reduction of the light intensity of the moving striations; and (4) complete elimination of the moving striations under certain operating conditions. Those who have noted these phenomena are in general agreement as to the reasons for them. Meissner and Miller (6) propose that the potential

change is due to the destruction of metastable atoms in the discharge.
Kenty (4), Donahue and Dieke (5), Pekarek (10) and Hakeem and Robertson
(9), all explain the other phenomena, as well as the potential change, by
such a process.

This work is undertaken for the purpose of attempting to corre-
late the effects observed in argon with those previously observed in neon
and mercury. In addition, a determination of the distribution of metastable
atoms throughout the positive column is attempted.

4.2 Technique for Measurement of Resonant Radiation Effects.

Fig. 14 shows the experimental arrangement used for the mea-
surement of changes induced in the various parameters of the experimental
discharge when illuminated with an external resonant radiation source.

With the irradiating source in position, but with light shields in
place to prevent illumination of the main discharge, current through the tube
and the potential across the tube were recorded. The frequency of the stria-
tions was read directly from the electronic counter and cross checked with
the frequency as presented on the oscilloscope by the photomultipliers. The
output of the photomultipliers was adjusted by varying the dynode voltage so
that the trace presented on the oscilloscope from the cathode end of the dis-
charge tube was equal in amplitude to the trace presented from the anode end.
The wavelength of the striations was read directly from the optical bench on
which the photomultipliers were mounted. This was accomplished by moving
one of the photomultipliers along the tube until the striation traces on the
dual beam oscilloscope were in phase. This position was noted and the
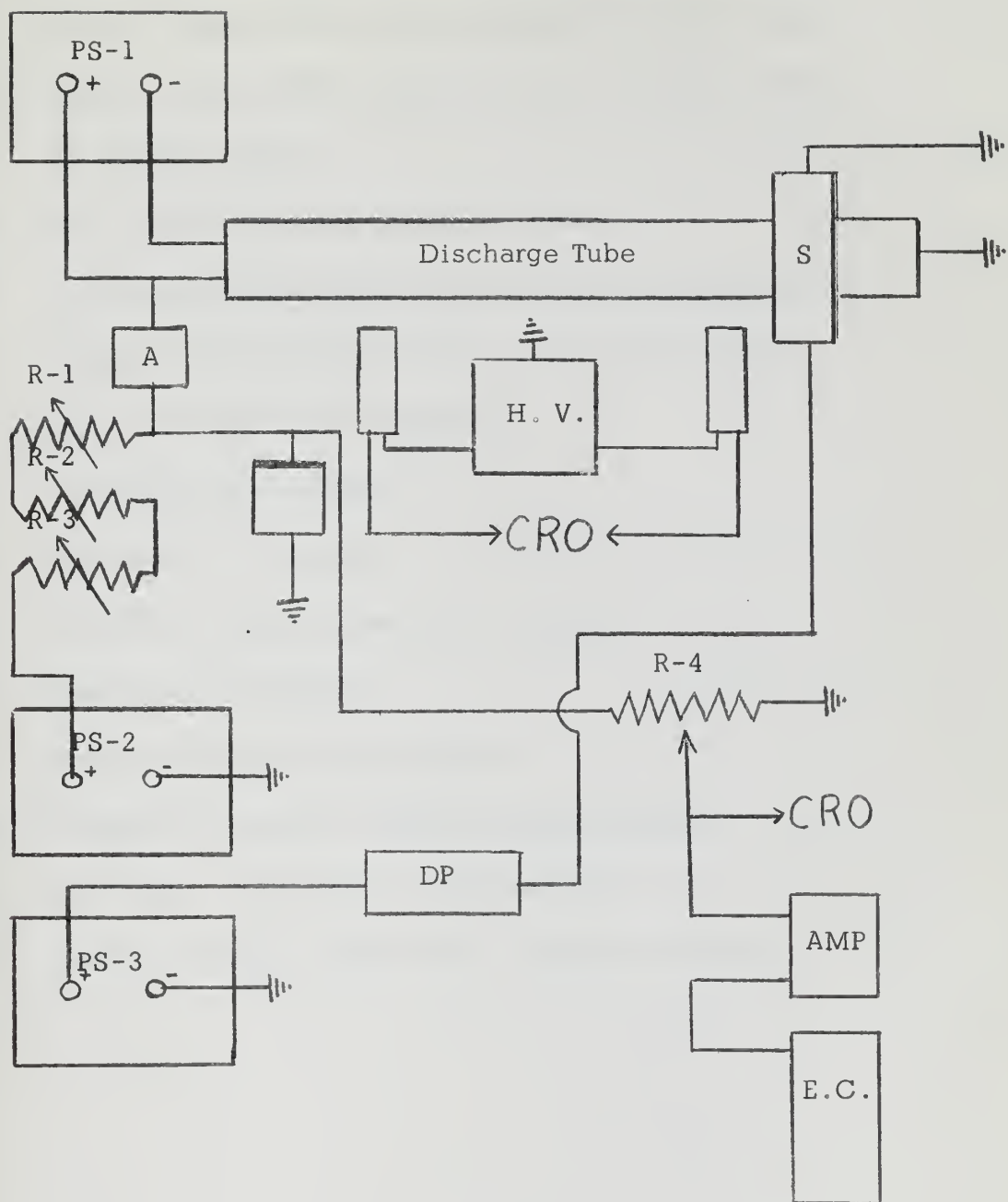
Fig. 14.

Experimental Arrangement For Measurement of Resonant Radiation
Effects.

LIST OF EQUIPMENT IN FIG. 14.

PS-1   Kepco, model 605, voltage regulated dc power supply.

PS-2   Kepco, model 770B, voltage regulated dc power supply

PS-3   Kepco, model 1250B, voltage regulated dc power supply

S   Irradiating source.

PM   RCA, type 7102, photomultiplier tube.

HV   4 Burgess U-200, series connected dry cell batteries

A   Weston Electrical Inst. Corp., model 622, ammeter.

V   RCA, model WV-98B, voltmeter.

R-1   Resistors, 94.2 kohms.

R-2   Resistors, 78.0 kohms.

R-3   Resistors, decade boxes, 555.5 kohms.

R-4   Resistor, 50 megohm.

DP   Source light distribution panel.

CRO   Tekronix, type 551, dual beam oscilloscope.

AMP   Scott Inc., type 140A, decade amplifier.

EC   Hewlett Packard, model 521C, electronic counter.

photomultiplier again moved until the two traces were again in phase. This was done a minimum of three times and an average wavelength determined for each operating condition of the discharge tube. The accuracy of these measurements is approximately ± 6%.

In this manner, while the discharge tube was not receiving any irradiation, the following measurements were recorded:

(a) Discharge current,

(b) Discharge potential,

(c) Striation frequency,

(d) Striation wavelength.

Following the above measurements, the light shields were removed, the current adjusted to its original value, and the values of the above quantities were again recorded where possible. (It should be noted that the frequency and wavelength were usually not measurable because the discharge was generally unstable when irradiated.) A third set of measurements was made with Corning Glass Works infra-red transmitting filters, C.S. No. 7-69, inserted between the irradiating source and the main discharge. The filters were then removed, the current adjusted to the original value, and the quantities measured again. This provided a check on the previous non-filtered measurements. Finally, the light shields were replaced and the current again adjusted to the original value. The original discharge conditions were duplicated at this time (discharge tube not receiving any irradiation) and the various quantities were again recorded as a check on the initial readings.

The irradiating source was then moved a specific distance down

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the discharge tube and the above process repeated. The distances moved

and the lengths of the positive column irradiated were varied. Using tube A

(see Fig. 2), one set of measurements was made irradiating only a 5 cm sec-

tion of the positive column at each position. Potential change measurements

were made at various currents, although the discharge was unstable during

most of these measurements. Measurements were made along the entire

length of the discharge tube when this could be done. This procedure was

carried out with tube A with discharge currents ranging from 0.57 ma to 1.5

ma at a pressure of 3.4 mm Hg.

The investigations conducted with Tube B (see Fig. 2) were

carried out at currents of 3.5 ma and 5.0 ma at a pressure of 6.6 mm Hg.

Measurements were made in this tube with a hot cathode and an anode dis-

charge of 250 ma, a cold cathode and the same anode discharge and with a

cold cathode and no anode discharge.

Initial investigations were conducted with tube A, using an ir-

radiating source of seven Central Scientific Co. argon spectrum tubes.

These tubes were mounted as shown in Fig. 15. A 5 by 8 cm section in the

base of the mount was removed and provision made for the insertion of a

light shield and the filter.

This irradiating source was not controllable as to the intensity

of the irradiation emitted. However, the results of these preliminary investi-

gations indicated that a more controlled experiment should yield considerably

more information on the nature of irradiative depopulation of the metastable

atoms in the discharge.
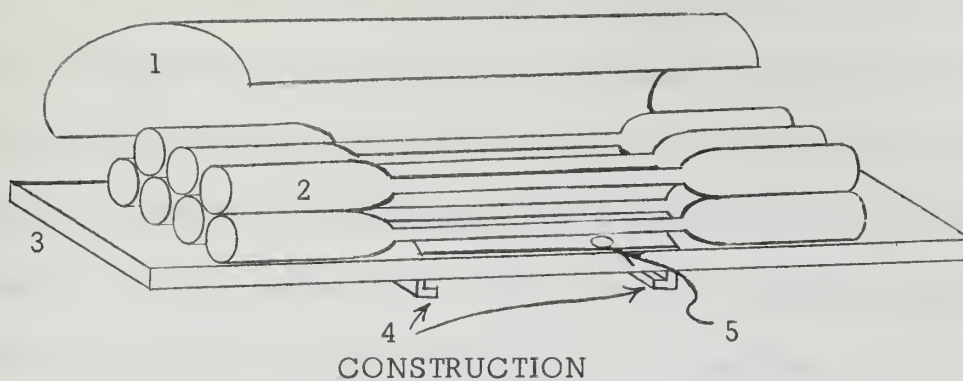
CONSTRUCTION

1. Light shield
2. Argon spectrum tubes
3. Mounting base
4. Slots for light shield and filter insertion
5. 5 x 8 cm opening
6. 7 100k ohm resistors

ELECTRICAL CIRCUIT
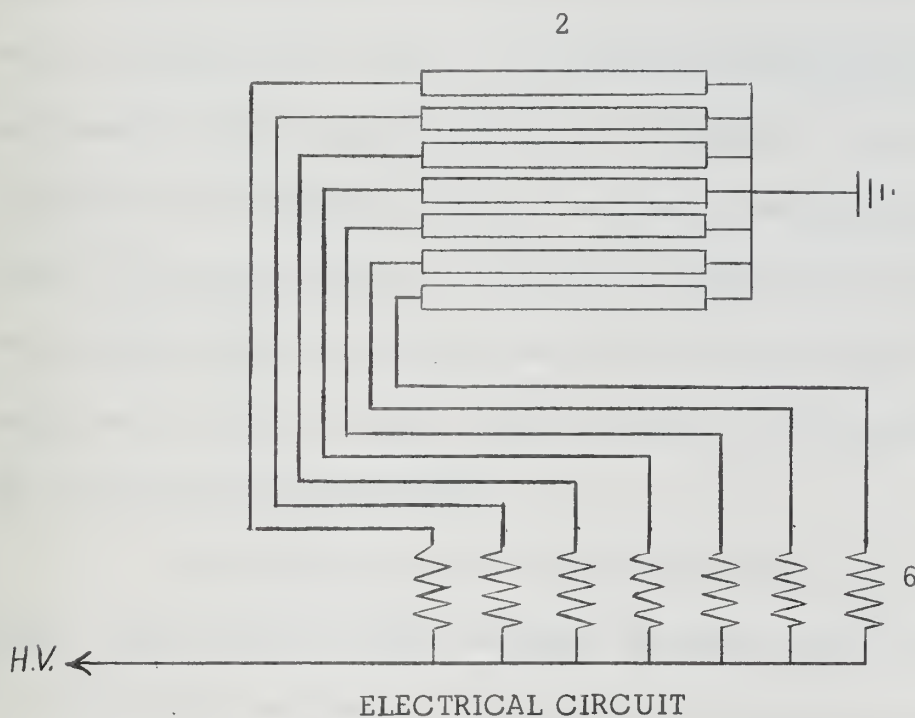
Fig. 15. Construction and electrical circuit for
irradiating source for discharge tube A.

The accuracy of the measurements made in this first attempt is in doubt, the errors could be as high as ± 20% in the potential change when the discharge was unstable. The frequency and wavelength change could be determined only when the discharge was stable and, under such operating conditions, the accuracy of all measurements is considerably increased. The ratio of the light intensity from the irradiating source to the average light intensity of the discharge was of the order of 20/1.

For more controlled investigations, a new irradiating source was constructed to permit accurate control of the source light intensity. This source consisted of twenty argon spectrum tubes arranged in four groups of five tubes each. The groups of tubes were mounted on a rectangular box with a 4 by 5 cm opening cut in each side to allow for irradiation over a 4 cm section of the positive column. The openings were fitted with slots to permit insertion of light shields and filters as required. To assure minimum dispersion of the irradiation to other sections of the discharge tube, a cardboard cylinder approximately 3 mm larger in diameter than the discharge tube, was inserted inside the mounting box and sealed at the openings to the irradiating source. Figs. 16 and 17 show the details of the irradiating source and the associated electrical circuit.

The electrical power to the spectrum tubes was supplied by a Kepco, model 1250 B, voltage regulated, dc power supply, which provided up to 1000 volts and 500 ma. Power from the supply was connected to a distribution panel with four 20 kohm variable resistors in parallel with the high voltage source. The output from each resistor was passed through a separate

1 Argon Spectrum Tube

ID of capillary = 1.5 mm
OD of capillary = 6.0 mm
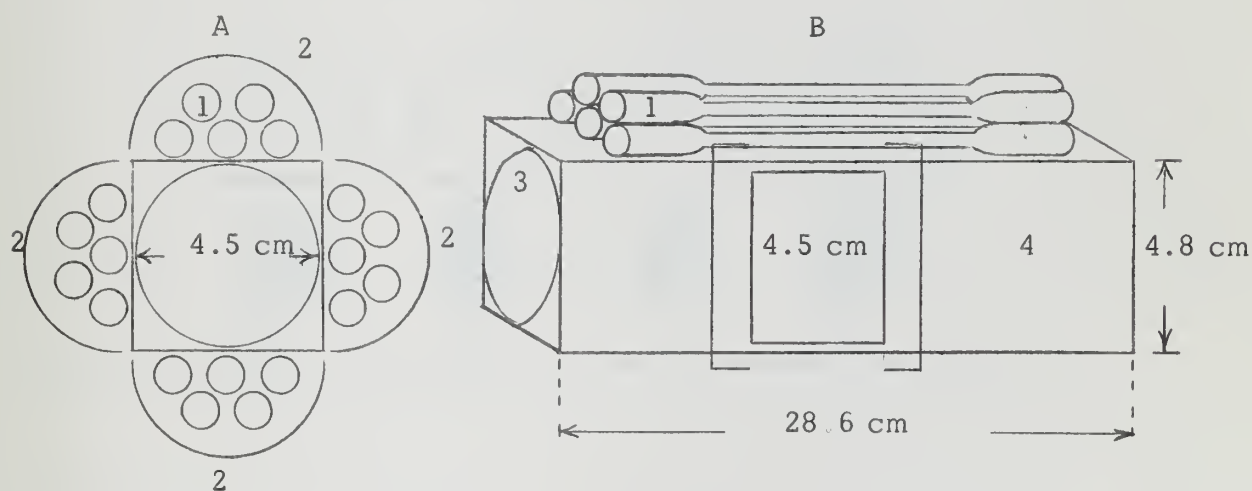ID of enlargement = 2.3 cm
OD of enlargement = 2.5 cm

2 Reflectors
3 Cardboard Cylinder
4 Mounting Box
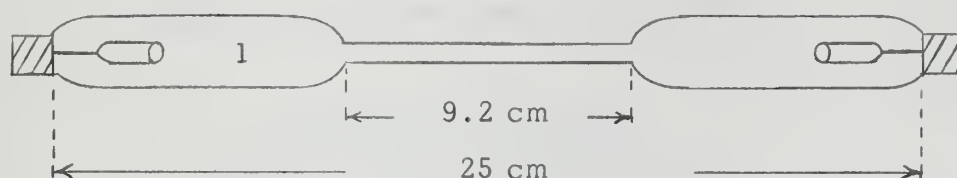
Single Argon Spectrum Tube

Construction of Irradiating Source

A End View

B Side View (only one irradiating source group shown)

Fig. 16. Irradiating Source Construction

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1 Argon Spectrum Tubes
2 Milliammeters (0-100 ma)
R_1 Resistors (50 kohm each)
R_2 Variable Resistors (0-20 kohm each)

Single Irradiating Source Group Shown
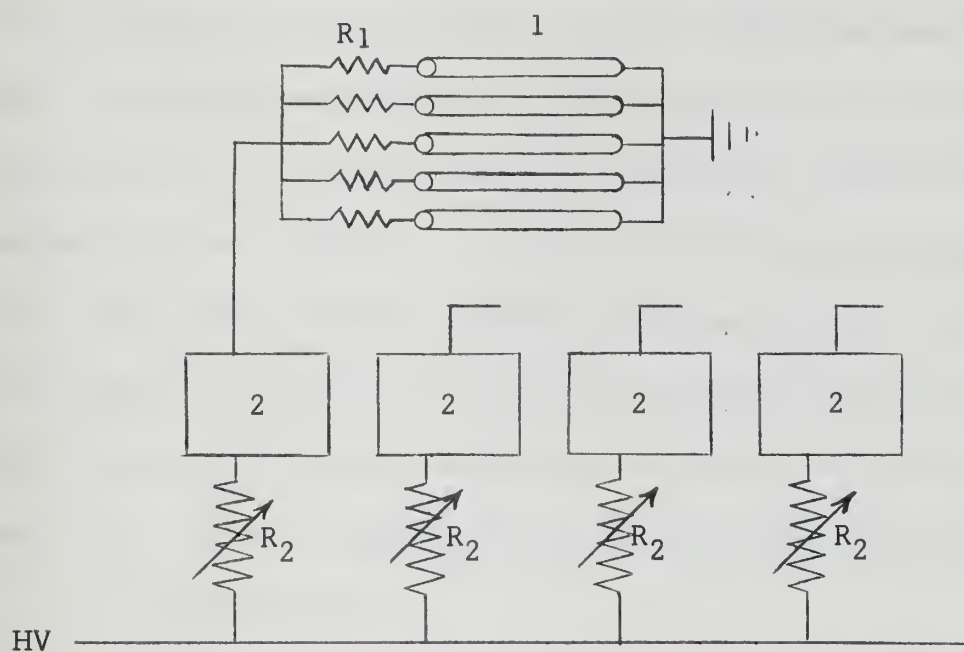
Fig. 17. Electrical Circuit for Controllable Irradiating Source.

milliammeter to one of the four groups of spectrum tubes. Each spectrum tube in a group was connected in parallel to the high voltage through a 50 kohm series resistance. The illumination level of each group could be controlled independently of the others by adjustment of the variable resistor on the distribution panel, the current passing through each group being read directly from the milliammeter.

By plotting the light intensity emitted from each group as a function of the current through the group, a direct relationship was obtained with which to determine the illumination level by adjusting the current flow to the desired value. On the same graph, the average light intensity from the main discharge tube was plotted as a function of the discharge current. By reference to this graph, the ratio of the light intensity from the irradiating source to the average light intensity from the main discharge was easily determined. The investigations carried out using this source were conducted with discharge tube B. Fig. 18 is the graph by which the illumination levels were determined.

4.3 Observations.

In discharge tube A, the potential change across the tube at constant current, when irradiating 5 cm sections of the positive column, is summarized in Fig. 19. In this discharge tube, there appears to be a large increase at the cathode end of the positive column and a rather uniform increase throughout the remainder of the column. It is of some interest to note the effect of increasing current on the position where the maximum increase in potential occurs. As the current is increased, this maximum appears to shift toward the cathode. This large increase may be due to several factors which will be

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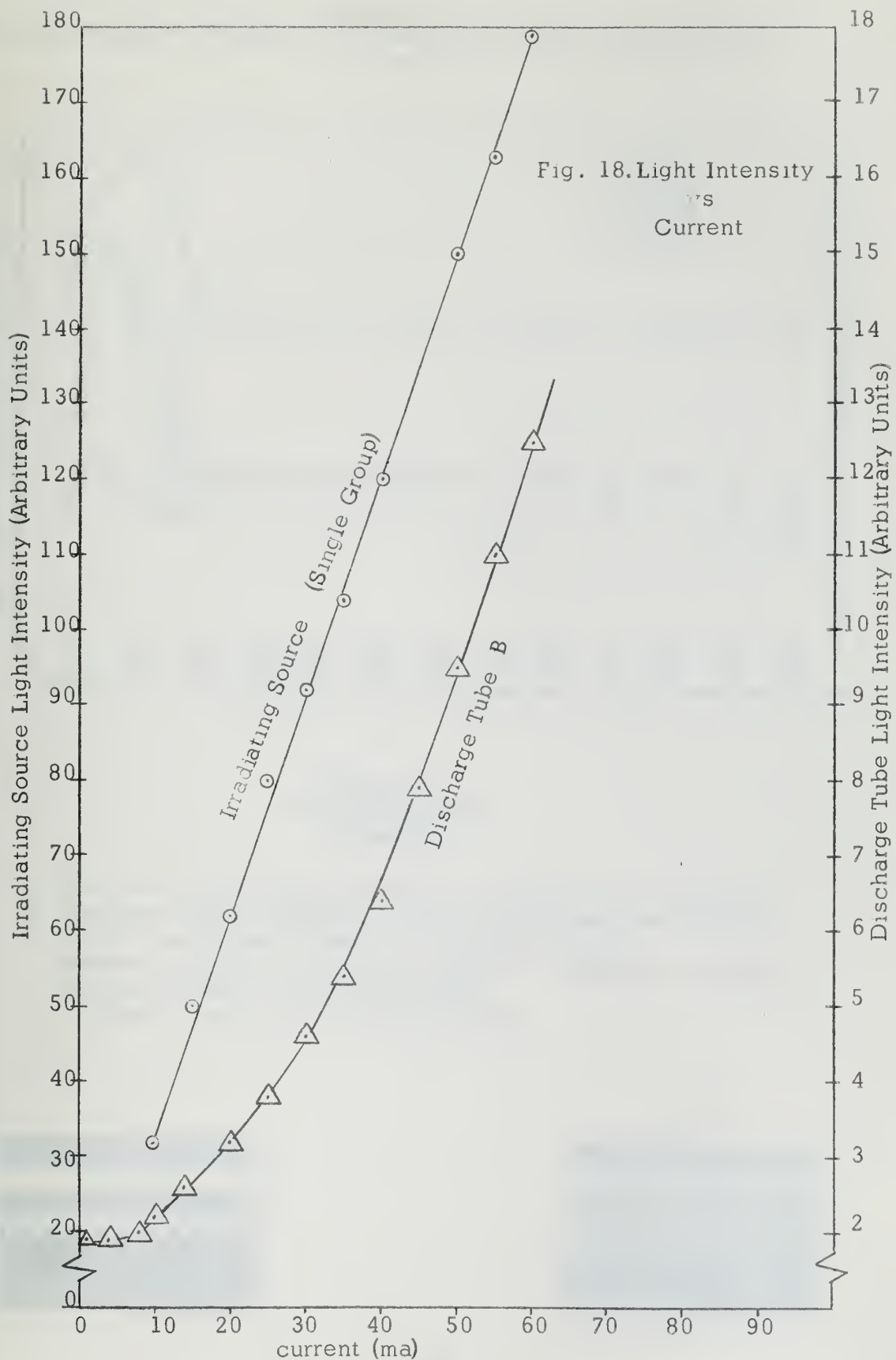Fig. 18. Light Intensity
vs
Current

Figure 19
Potential Change vs Position of Irradiating Source. Discharge Tube A
3.4 mmHg

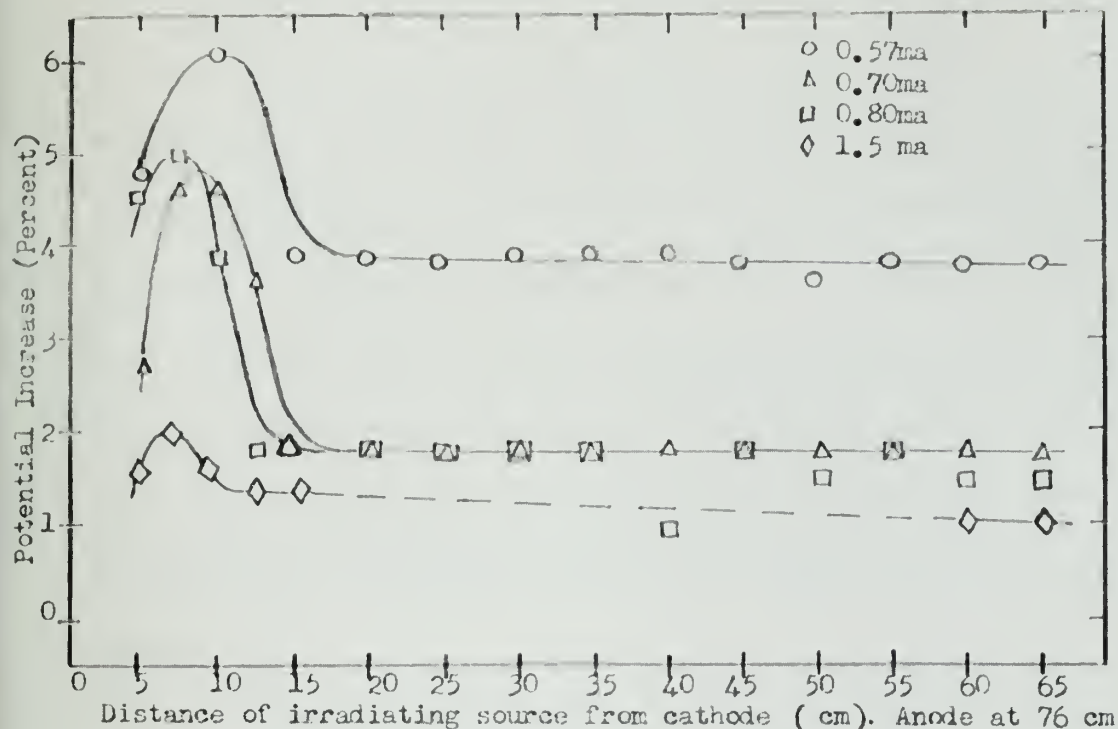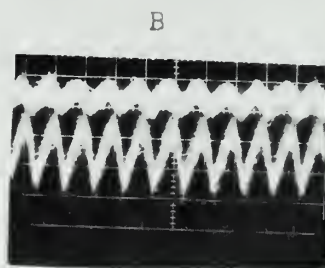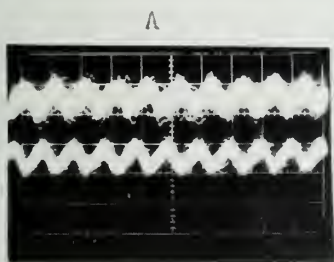Figure 20
Striation Light
Intensity

A Striation light intensity with no illumination from source.
B Striation light intensity after illumination from source.
   Lower trace directly under illuminating source.
   Discharge Tube A   Current = 0.65 ma   Pressure = 3.4 mmHg
   Vertical scale = 200 microvolts/cm
   Horozontal scale = 0.5 milliseconds/cm

discussed further in the analysis section of this report.

The intensity of the irradiating source used for investigations on this discharge tube was not controllable. The main discharge was operated only with a cold cathode and without an anode discharge. The discharge would become unstable whenever it was irradiated except when operating at a current of 0.65 ma. Even in this case, the discharge would degenerate to an unstable condition when irradiated within 15 cm of the cathode. Under such conditions, the accuracy of the measurements made is in doubt. Beyond the area extending to approximately 15 cm from the cathode, the discharge would remain stable when illuminated only at a current of 0.65 ma. Throughout this region, the potential increase for a given current was relatively uniform.

When the discharge did remain stable while illuminating it with resonant radiation, the striation frequency and wavelength could be measured. The general effect of illumination was to increase both the frequency and wavelength, and therefore the velocity of the striations. Fig. 21 shows the effect on these parameters in discharge tube A. Since all of these parameters are related, only the change in wavelength and velocity are shown. There is a rather large increase in these parameters observed at a distance between 20 and 25 cm from the cathode, the increase rising to a maximum at this point and then decreasing to a constant value from approximately 40 cm from the cathode to the anode.

One of the most interesting observations made in discharge tube A at 0.65 ma is shown in Fig. 20. Directly under the irradiating source at all positions along the positive column, the amplitude of the light intensity

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Fig. 21. Change in striation parameters vs position of irradiating source.

Discharge tube A at constant current (0.65 ma) and 3.4 mm Hg.

Distance of irradiating source from cathode (cm)
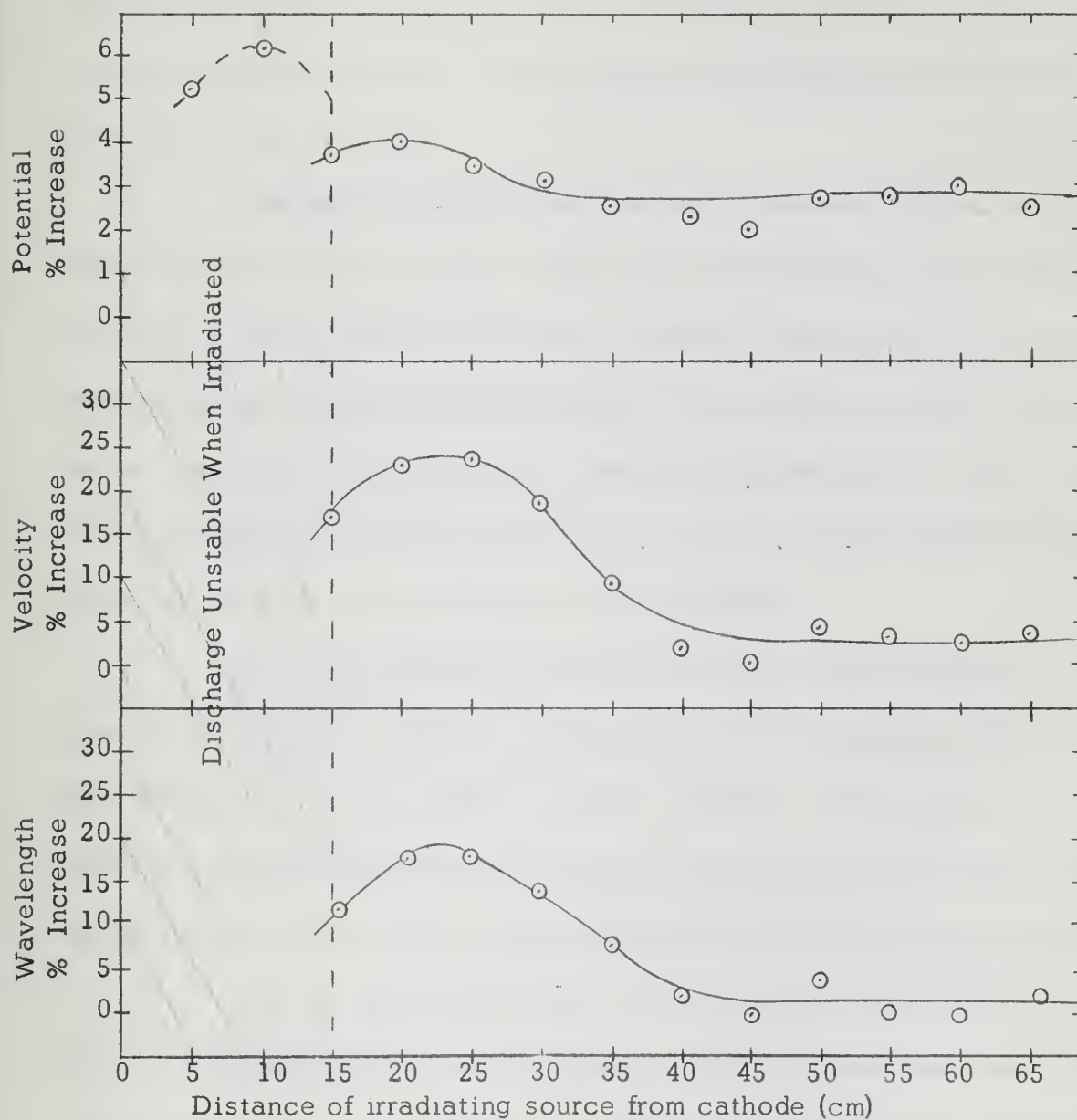
Anode at 76 cm from cathode. Discharge operated with cold cathode and no anode discharge.

from the moving striations was almost tripled while that from other sections

of the discharge tube was apparently not affected. This large increase was

observed to diminish to the amplitude of the light intensity from the stria-

tions in other sections of the discharge within approximately 3 cm to either

side of the irradiating source. Since the discharge would not remain stable

at other operating currents, this phemomenon could not be investigated ex-

cept at 0.65 ma in tube A.

The investigations conducted using discharge tube B provided

more reliable potential change results since the discharge would remain

stable over a wider range of currents. However, measurements of frequency

and wavelength changes were abandoned, after several attempts, since the

current could not be stabilized for a sufficiently long period of time. Also,

the length of the irradiating source was such that accurate measurements

could not be made at all positions in the discharge.

The light intensity from the irradiating source used in the inves-

tigations on discharge tube B was completely and accurately controllable

from illumination ratios of 15/1 to ratios of 300/1. In this report, the illum-

ination ratio will be defined as the ratio of the light intensity from the irrad-

iating source to the average light intensity from the experimental discharge.

Fig. 22 shows the effect on the potential increase due to filter-

ing the irradiation from the source tubes. The filters used were those de-

scribed in Section 4.2. The range of wavelengths passed by these filters is

shown in Fig. 11. The slight decrease in the potential change using the

filters is accounted for by considering the attenuation by the filters of the
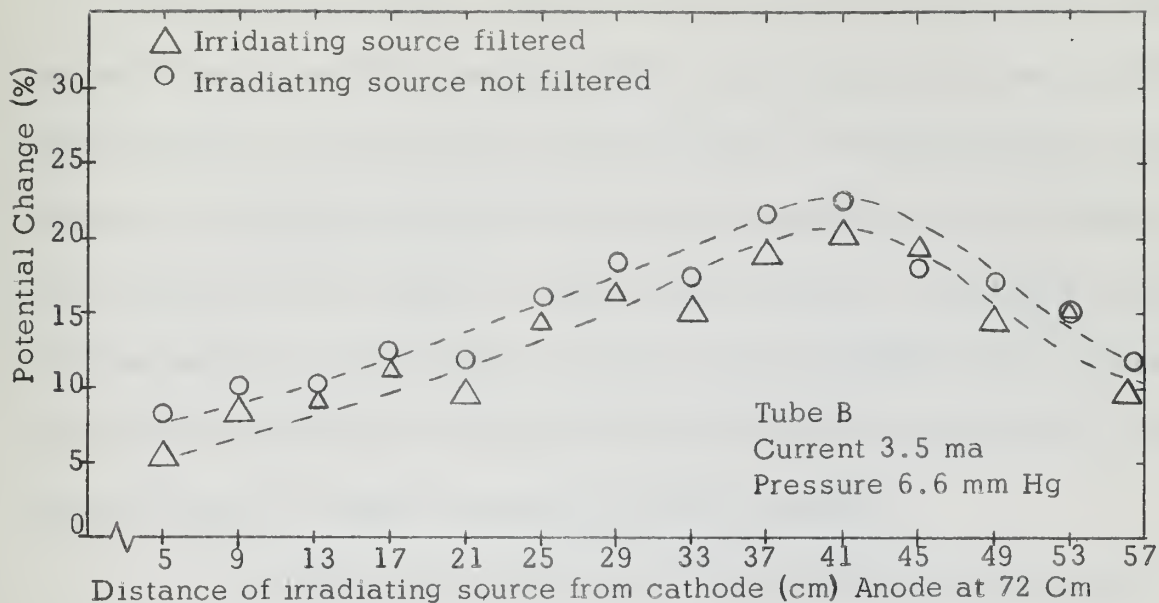
55

Fig. 22. Potential Change vs Irradiating Source Position.
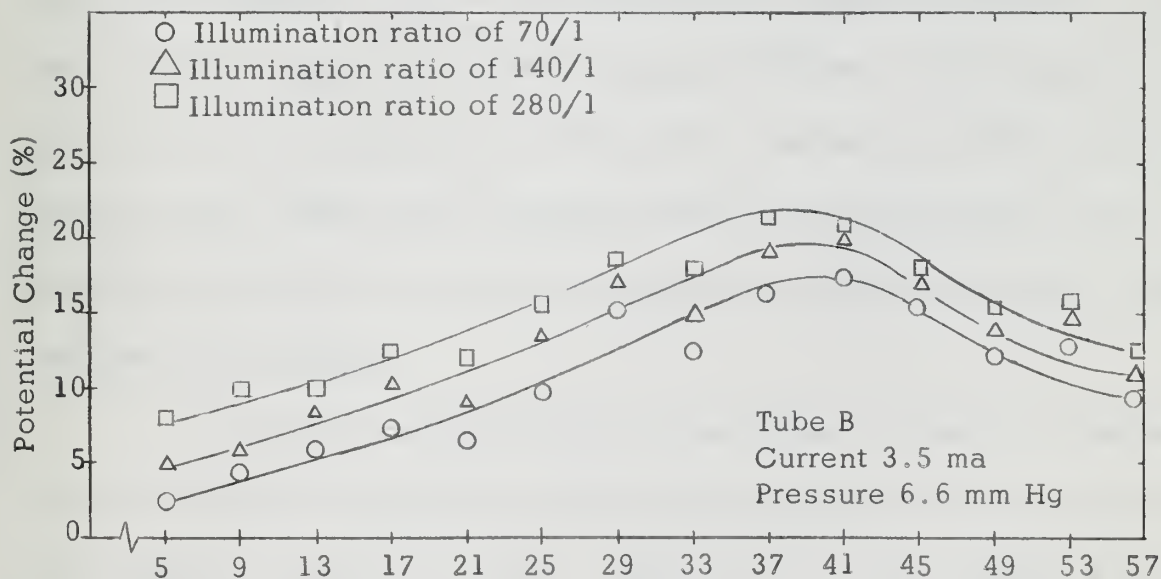Illumination ratio 280/1, hot cathode and an
anode discharge of 200 ma.

Fig. 23. Potential Change vs Irradiating Source Position.
Hot cathode and an anode discharge of 200 ma.

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resonant wavelengths from the source.

Fig. 23 demonstrates the effect of increasing irradiation intensity on the potential change. The potential increase is approximately 2% for each doubling of the illumination ratio in the region of the positive column extending from the cathode end to the point of maximum increase. From the point of maximum increase in potential on toward the anode, doubling the illumination ratio appears to exert a lesser effect. It should be noted that increasing the illumination ratio also had less effect on the amplitude of the light intensity from the moving striations in the region of the positive column beyond the point of maximum potential increase.

The effect of a hot cathode on the potential increase across the discharge tube after irradiation was found to be considerable. Fig. 24 shows the potential increase observed with a cold cathode vs the potential increase observed with a hot cathode. Also depicted on this graph are the results obtained while operating with a cold cathode and no anode discharge. The latter case is a duplication of the operating conditions of discharge tube A and, except for the abrupt rise in the curves of potential increase derived from that tube, shows good correlation between the two discharge tubes. Discharge tube B was also always unstable after illumination when no anode discharge was running.

Fig. 25 is a demonstration of the degree to which the illumination ratio could be controlled with the irradiating source constructed for the investigations in discharge tube B. Referring to Fig. 18 in Section 4.2, it is readily seen that an illumination ratio of 140/1 can be achieved with four
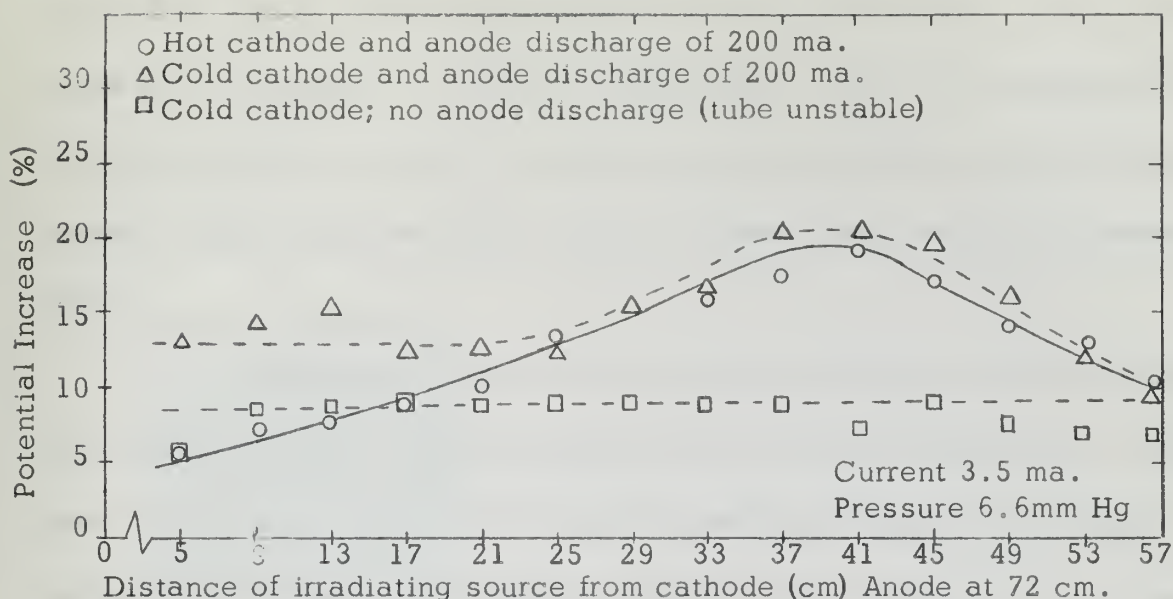
57

Fig. 24.
Potential Change vs Irradiating Source Position.
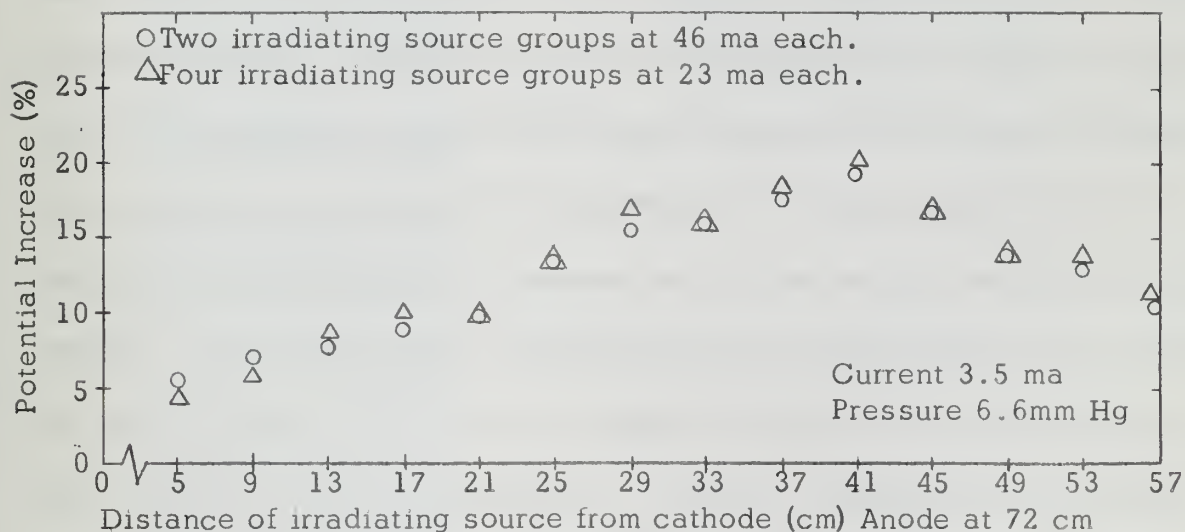Illumination ratio 140/1; Tube B; Constant current.

Fig. 25.
Controlability of Irradiating Source.
Illumination ratio 140/1; Tube B.

irradiating source groups operated at a current of 23 ma each, or with two such groups operated at a current of 46 ma each. This can be applied to other illumination ratios as well. In both cases mentioned above, the potential increase is practically the same, and in any case, well within experimental error.

The effects produced on the moving striations when the discharge was illuminated were very pronounced and completely reproducible. In general, the striation light amplitude was decreased throughout the positive column with increasing illumination intensity, the decrease always being greatest where the potential increase was greatest. In the regions of the discharge tube where the potential increase exceeded approximately 12%, the striations could be destroyed entirely throughout the positive column (within the detection capability of the equipment used) with sufficient illumination intensity. Fig. 26 shows the effect of increasing illumination intensity on the amplitude of the light intensity emitted by the moving striations. It is interesting to note that the amplitude of the light intensity from the moving striations appears to decrease first at the cathode end of the positive column. This is the general observation when operating with a hot cathode. On the other hand, the decrease is equal throughout the positive column when operating with a cold cathode. A possible explanation of this phenomenon will be discusssed in the analysis section of this report. The oscilloscope pictures in Fig. 26 were taken with the irradiating source at a position 33 cm from the cathode. The photomultiplier tubes were at equal distances from the irradiating source.

Striation Light Intensity

Illustration of decreasing light intensity from moving striations
with increasing illumination from resonant source. Discharge
operated with a hot cathode and an anode discharge of 200 ma.
Discharge Tube B at a current of 3.5 ma and a pressure of 6.6 mm.
Photographs taken with the irradiating source at a position 33 cm
from the cathode. Photomultiplier
tubes were at equal distances from
the irradiating source. Upper trace
is from the cathode end of the
positive column, lower trace from
the anode end of the positive column.

Vertical Scale: 100 microvolts/cm
Horozontal Scale: 0.5 millisec/cm
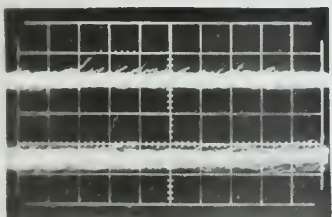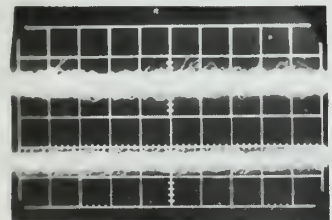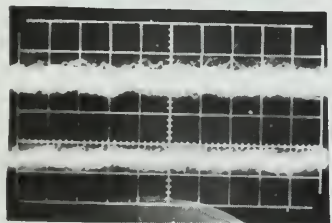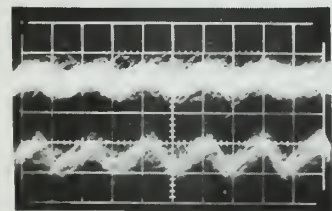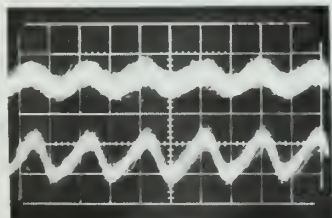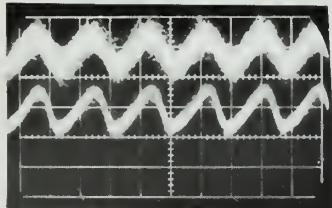
A.   No Illumination
B.   Illumination ratio of   70/1
C.   Illumination ratio of   140/1
D.   Illumination ratio of   210/1
E.   Illumination ratio of   280/1
F.   Photomultiplier dark current noise.

While operating the discharge with a cold cathode, but with an anode discharge of 250 ma, the striations could be destroyed at any position of the irradiating source along the positive column that could be reached. The connection from the discharge tube to the vacuum system prevented irradiation of the positive column beyond 57 cm from the cathode. The striations were again observed to be most sensitive to resonant radiation where the greatest increase in potential occurred.

No analysis of the striation behavior could be made when operating without an anode discharge as the main discharge would always become unstable when irradiated.

With a discharge current of 5.0 ma, another interesting phenomenon occurred when the positive column was irradiated at a position 29 cm from the cathode. With an illumination ratio of 70/1, the amplitude of the light intensity from the moving striations was observed to increase when the discharge was illuminated. When the illumination ratio was doubled, the amplitude decreased in mcuh the same manner as was observed at the lower current. With the irradiating source 4 cm to either side of the above position, no such effect was observed. Fig. 27 shows the occurrence of this phenomenon as contrasted with the effect observed at a position 4 cm beyond the position referred to above.

When standing striations were present in the positive column of the discharge, very large increases in tube potential, along with a large reduction in discharge current, were observed whenever one or more of these striations was illuminated with resonant radiation. With a relatively low

Figure 27

Striation Light Intensity

Different phenomena occuring within 4 cm of each other in Discharge
Tube B at a pressure of 6.6 mmHg and a current of 5 ma. The
discharge was operated with a hot cathode and an anode discharge of
200 ma. Upper trace is from the cathode end of the positive column.
Lower trace is from the anode end of the positive column. Note the
increase in the striation light intensity at position 29 when
irradiated with an illumination ratio of 70/1.

Distance of Irradiating
Source From Cathode

Distance of Irradiating
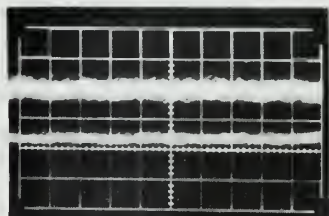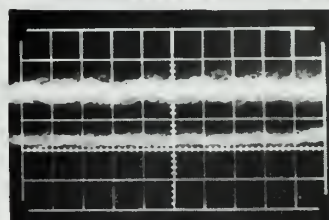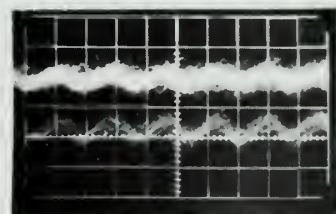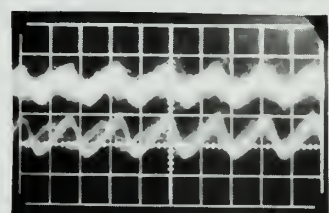Source From Cathode

29 cm

33 cm

Illumination
Ratio

0

70/1

140/1

210/1

280/1
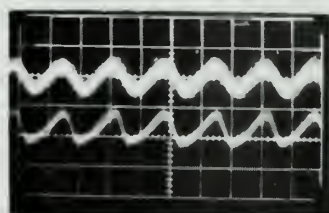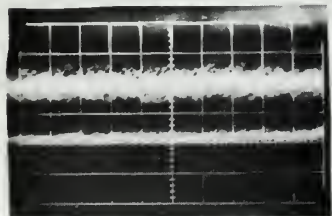
illumination ratio, approximately 20/1. the discharge would be extinguished immediately when illuminated while operating at currents up to 13 ma. This occurred with a 1000 volt supply to the discharge t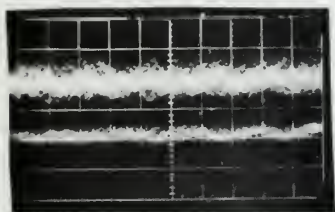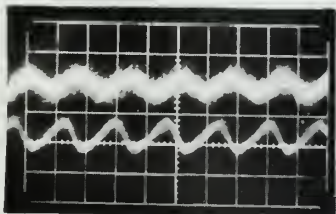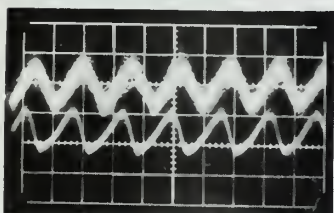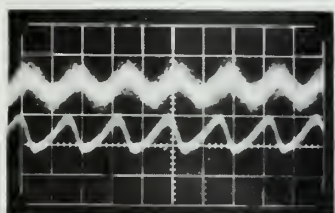ube with appropriate resistance in series to limit the current. The pressure in the discharge tube at this time was 3.6 mm Hg. At 14 ma, the percent increase in tube potential was as high as 15% with an illumination ratio of 20/1. Other phenomena such as bending of the positive column, increasing the number of standing striations in the positive column, removing the standing striations directly under the irradiation and several others were observed when the discharge was irradiated. Investigation of these phenomena was not pursued since the primary goal of this work was concerned with moving striations.

4.4 Analysis of Observations.

The potential increase associated with the illumination of the discharge by resonant radiation is apparently due to irradiative depopulation of metastable atoms. This is demonstrated by the fact that the entire increase in potential can be attributed to radiation by only those wavelengths associated with the metastable transitions while filtering out wavelengths outside of this range. This is shown in Fig. 22.

In discharge tube A, the large increase in potential observed at the cathode end of the positive column when irradiated may have been due to the formation of standing striations in that region of the discharge. The development of standing striations near the cathode is not uncommon at low pressures, as is shown by Cooper (13) in neon. At very low currents these striations are not normally visible to the naked eye.

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When operating discharge tube A at 0.65 ma, the potential in-crease beyond the region of instability (Fig. 21) is relatively uniform through-out the positive column. There appears to be a slight increase in the poten-tial change in the same region where the velocity and wavelength of the moving striations show a marked increase.

The increase in light intensity of the moving striations directly under the irradiating source in discharge tube A (Fig. 20) can be explained on the basis of Robertson's theory (3) and his latest published work (9), and the statement made by Donahue and Dieke (5) that the velocity of the stria-tions is greatest when the light intensity is brightest.

In Robertson's theory (3) (9), the product of the metastable con-centration (M) and the derivative of the electron density function (df/dn), appears as the controlling factor in the production of instabilities within the positive column which lead to moving striations. This product (M df/dn) is defined by Robertson as the ionization rate per unit volume of metastable atoms (9). According to Robertson, moving striations are expected when this product is sufficiently positive. Also, the frequency of the striations should increase with an increasingly positive ionization rate per unit volume of metastable atoms. In this work, the frequency and the velocity of the moving striations were shown to increase under the influence of a relatively weak illumination ratio in discharge tube A (see Fig. 21). In reference (9), Robert-son shows that in the low current regions, the product M df/dn can actually increase while the metastable concentration M is decreased.

This explanation can also be applied to the increased striation

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light intensity observed throughout the discharge in tube B under the influ-
ence of a relatively weak illumination ratio and a current of 5.0 ma (see
Fig. 27). No prediction can accurately be made as to when such a pheno-
menon should be observed, as neither the form of the electron density func-
tion, F(n), in Robertson's theory nor the actual metastable concentration is
known.

Under other illuminating and operating conditions, the general
effect of illumination by resonant radiation was a decrease in the striation
light intensity with increasing illumination intensity. This decrease could
be carried to the point where striations, if present, were not detectable above
the noise level of the photomultiplier tubes. This would be the result nor-
mally expected when irradiative depopulation was occurring, according to
Robertson.

The increase in the potential change in the cathode region of the
discharge when operating with a cold cathode (Fig. 24) can also be explained.
It is believed that this increase, as much as 9% above the increase observed
when operating with a hot cathode, is due to irradiative depopulation of the
metastable atoms in that region by radiation emitted from the hot cathode.
This is also a possible explanation for the disappearance of the striations
at the cathode end of the positive column first as the cut-off current is ap-
proached as shown by Cooper (13) and Oleson and Cooper (15). The explana-
tion applies equally well to the fact that the striation light intensity was ob-
served to decrease first at the cathode end of the positive column (Fig. 26)
when operating with a hot cathode. This phenomenon was not observed when

the discharge was operated with a cold cathode. The color temperature of the cathode in this experiment was estimated to be approximately 3000°K.

5. Conclusions

5.1   Conclusions.

The metastable concentration in argon appears to exert a large influence on the behavior of moving striations in the range of pressures and currents investigated in this experiment. This is substantiated by the increase in discharge tube potential when the discharge was illuminated with the resonant wavelengths necessary for irradiative depopulation of the metastable states of argon. Additionally, this conclusion is supported by the fact that the moving striations were most sensitive to resonant radiation in the regions where the potential increase was greatest. This conclusion gains additional support from the results of the experiments using a hot cathode and a cold cathode. Fig. 24 would tend to support the conclusion that radiation from a hot cathode reduces the metastable atom concentration in that region of the discharge. Therefore, the effects observed in that region, when irradiated with an external resonant source, are considerably less than those observed while operating with a cold cathode.

The stability of the discharge also appears to have a large effect on the potential increase when the discharge is illuminated. When the discharge is unstable, the potential increase is relatively constant throughout the positive column and less than the increase observed when the discharge is stable.

In these investigations, the metastable concentration appears to reach a maximum value near the center of the positive column under stable operating conditions. This conclusion is based on the results of the potential

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increase as a function of the distance along the positive column when ir-radiated with the resonant wavelengths necessary to cause irradiative de-population of the metastable atoms in argon. It is supported by the fact that the effects produced on the moving striations, by resonant radiation, are greatest where the potential increase is greatest. Fig. 24 could be interpreted as a very rough indication of the metastable concentration through-out the positive column under the various discharge conditions.

Standing striations appear to contain large concentrations of meta-stable atoms. This is supported by the fact that the illumination of a single standing striation produces a much greater potential increase for a given il-lumination ratio, than is normally experienced when they are not present.

In general, the results of this experiment lend added support to the Robertson theory of moving striations. Many of the effects observed in this experiment can be predicted from this theory of moving striations.

5.2 Recommendations for Further Work.

In view of the limited range of currents and pressures investigated in this experiment, it is recommended that further investigations be carried out over a wider range of discharge conditions. Also, a shorter irradiating source would permit irradiation further along the discharge tube than was possible in this experiment. Such a source could be constructed by using a long capillary tube wound around the main discharge tube. The illumination intensity of the irradiating source should be controllable.

The effect of the hot cathode should also be investigated further. This may be accomplished by designing a discharge tube with a side arm

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cathode, shielded to prevent radiation from the hot cathode from propagating down the positive column.

The problem of major interest is to determine the time rate of change of metastable atom concentrations within a striated glow discharge. A possible technique for determining such a quantity is outlined in Section 3.4 of this report.

5.3 Acknowledgements.

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